LIGHT EMITTING ASSEMBLY

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. Patent Application No. 09/604,056, entitled "LED ASSEMBLY," filed on June 26, 2000, by Robert R. Turnbull et al., which is a

5   continuation of U.S. Patent Application No. 09/148,375, entitled "ILLUMINATOR ASSEMBLY INCORPORATING LIGHT EMITTING DIODES," filed on September 4, 1998, by Robert R. Turnbull et al., now U.S. Patent No. 6,132,072, which is a continuation of U.S. Patent Application No. 08/664,055, entitled "ILLUMINATOR ASSEMBLY INCORPORATING LIGHT EMITTING DIODES," filed on June 16, 1996, by Robert R.

10   Turnbull et al., now U.S. Patent No. 5,803,579. The entire disclosures of both the above applications are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The present invention relates to a light emitting assembly incorporating light sources, and more particularly to white-light emitting assemblies.

15   Due to limitations in human vision in low light level environments, white-light illuminator systems have long been used to produce artificial illumination and enhance visibility during nighttime or overcast conditions or within interior quarters obscured from the reach of solar illumination. Illuminators are therefore generally designed to mimic or reproduce daytime lighting conditions, to the extent possible, so that illuminated subjects of

20   interest are bright enough to be seen and have sufficient visual qualities such as color and contrast to be readily identifiable.

A diversity of illuminator systems such as stationary lamps in buildings, portable flashlights, and vehicular headlamps and courtesy lights have evolved throughout history and have traditionally produced white light for general, spot, or flood illumination, using a variety of sources such as candles, oil, kerosene, and gas burning elements, incandescent and halogen bulbs, and fluorescent and other arc-discharge lamps. White light is critical in such uses because of its unique ability to properly render colored objects or printed images relative to one another and its similarly unique ability to preserve luminance and color contrast between adjacent objects or printed images having different colors. For instance, a blue photographic image of an ocean panorama will be readily distinguished by an unaided observer from black photographic images of volcanic rocks when the photograph containing these images is illuminated by white light. The two images would be, however, virtually indistinguishable from one another if illuminated with a deeply red-colored illuminator. Another example arises from the need to properly identify differently colored regions on conventional aeronautical or automotive maps. On an automotive map, white-light illuminators make it easy to discern the difference between the yellow markings for urban regions and the surrounding white rural areas. A deeply yellow-colored illuminator would make this distinction virtually impossible. On an aeronautical chart, white-light illuminators make it possible to discern the difference between the characteristic blue markings for certain types of controlled airspace and the green pattern of underlying terrain, whereas a deeply red-colored illuminator would make this distinction virtually impossible.

Furthermore, these issues of color discrimination and contrast go beyond the simple need for accurate identification. It is, for example, a well-known fact that high contrast is

critical for avoiding severe operator eye fatigue and discomfort during prolonged visual tasks, whether the subject of study is a book, magazine, newspaper or a map. White-light illuminators provide more universally high contrast and good color discrimination, thereby avoiding these annoying and dangerous physiological side effects.

5   The extensive evolution and widespread use of white-light illuminators, along with rapidly advancing technology and a phenomenon known as "color constancy," have fostered acceptance of a rather broad range of unsaturated colors as "white." Color constancy refers to the well-known fact that the level and color of slightly unsaturated or near-white illumination over an area can vary moderately without substantially altering the perceived colors of objects

10   in that setting relative to one another. An example of this is the appearance of an outdoor scene to an observer wearing slightly amber or green sunglasses. After a brief moment of adaptation upon donning the sunglasses, an observer becomes unaware that the scene is being passed through a slightly colored filter. Another example is the tacit acceptance of a wide variety of "white" illuminators in residential, commercial, and public illumination. The bluish

15   or cool white from various fluorescent lamps is virtually universal in office buildings, whereas the yellowish or warm white of incandescent lamps is dominant in residential lighting. The brilliant bluish-white of mercury vapor and metal halide lamps is commonplace in factory assembly lines, whereas the bronze-white emission of the high-pressure sodium lamp dominates highway overhead lighting in urban areas. Despite the discernible tint of each of

20   these sources which would be evident if they were compared side by side, they are generally accepted as white illuminators because their emissions are close enough to an unsaturated white to substantially preserve relative color constancy in the objects they illuminate. In other

words, they render objects in a manner that is relatively faithful to their apparent "true" colors under conditions of natural illumination.

There are limits to the adaptability of human color vision, however, and color constancy does not hold if highly chromatic illuminators are used or if the white illumination observed in a setting is altered by a strongly colored filter. A good example of this limitation can be experienced by peering through a deeply colored pair of novelty sunglasses. If these glasses are red, for instance, then it will be nearly impossible to discern a line of red ink on white paper, even though the line would stand out quite plainly in normal room illumination if the glasses are removed. Another illustration of this effect is the low-pressure sodium lamp used for certain outdoor urban illumination tasks. This type of lamp emits a highly saturated yellow light which makes detection and or identification of certain objects or printed images very difficult if not impossible and, consequently, their commercial use has been very limited. As will be discussed later, a similar problem arises from prior art attempts to use high intensity red or amber light emitting diodes (LEDs) as illuminators since they, like the low-pressure sodium lamp, emit narrow-band radiation without regard for rendering quality.

In order to improve the effectiveness of white-light illumination systems, various support structures are typically employed to contain the assembly and provide energy or fuel to the incorporated light source therein. Furthermore, these systems typically incorporate an assortment of optical components to direct, project, intensify, filter, or diffuse the light they produce. A modern vehicle headlamp assembly, for instance, commonly includes sealed electrical connectors, sophisticated injection-molded lenses, and molded metal-coated reflectors which work in concert to collimate and distribute white light from an incandescent, halogen,

or arc-discharge source. A backlight illuminator for an instrument panel in a vehicle or control booth typically contains elaborate light pipes or guides, light diffusers, and extractors.

Of course, traditional white-light sources, which generate light directly by fuel combustion, are no longer suitable for most vehicular, watercraft, aircraft, and portable and certain other applications where an open flame is unsafe or undesirable. These, therefore, have been almost universally superseded by electrically powered, white-light sources. Furthermore, many modern electric light sources are relatively inefficient, *e.g.*, conventional tungsten incandescent lamps, or require high voltages to operate, *e.g.*, fluorescent and gas discharge lamps, and therefore are not optimal for vehicular, portable, and other unique illuminators used where only limited power is available, only low voltage is available, or where high voltage is unacceptable for safety reasons.

Because no viable alternatives have been available, however, illuminators for these overland vehicles, watercraft, aircraft, and the other fields mentioned have used low-voltage incandescent white-light illuminators for quite some time to assist their operators, occupants, or other observers in low-light level situations. In automobiles, trucks, vans and the like, white-light illuminators are used as dome lights, map lights, vanity mirror lights, courtesy lights, headlamps, back-up lights and illuminators for the trunk and engine compartments and license plate. In such vehicles, white-light illuminators are also used to backlight translucent screen-printed indicia such as those found in an instrument cluster panel, door panel, or heater and ventilation control panel. Similar uses of white-light incandescent illuminators are found on motorcycles, bicycles, electric vehicles, and other overland craft. In aircraft, white-light illuminators are used in the passenger compartment as reading lamps to illuminate the floor

and exits during boarding, disembarking, and emergencies, to illuminate portions of the

cockpit, and to backlight or edge-light circuit breaker panels and control panels. In watercraft

such as ships, boats, and submarines, white-light illuminators are used to illuminate the

bridge, the decks, the cabins, and engineering spaces. In portable and specialty lighting

applications, low-voltage white-light illuminators are used as hand-held battery-powered

flashlights, as helmet-mounted or head-mounted lamps for mountaineering or mining, as

automatically-activated emergency lighting for commercial buildings, as task lighting in

volatile environments, and as illuminators in a wide variety of other situations where extreme

reliability, low voltage, efficiency, and compactness are important.

These aforementioned white-light illuminators rely almost exclusively upon

incandescent lamps as light sources because incandescent bulbs are inexpensive to produce in a

wide variety of forms and, more importantly, they produce copious quantities of white light.

Despite this, incandescent lamps possess a number of shortcomings, which must be taken into

account when designing an illuminator assembly.

Incandescent lamps are fragile and have a short life even in stable environments, and

consequently must be replaced frequently at great inconvenience, hazard, and/or expense.

This need for replacement has complicated designs for all manners of illuminators, but

especially for vehicles. For example, U.S. Patent No. 4,087,096 issued to Skogler et al.

discloses a carrier module for supporting lamps for illuminating a portion of a vehicle interior.

The carrier module has a rigid body and a pair of mounting projections for removably

mounting the carrier module in a rearview mirror. The design even has an opening

specifically designed to allow insertion of a tool for releasing the module from the rearview

mirror. This carrier module is an excellent example of the Herculean design efforts taken by mirror manufactures to ensure incandescent lamps can be easily removed and replaced by a vehicle owner.

In addition to their inherently short life, incandescent lamps are very susceptible to damage from mechanical shock and vibration. Automobiles experience severe shocks and significant vibration during driving conditions which can cause damage to incandescent lamps, particularly the filaments from which their light emissions originate. This is an especially severe problem for lamps mounted on or near the engine hood, trunk lid, passenger doors, exterior mirrors, and rear hatch or gate, all of which periodically generate tremendous shocks upon closing. Aircraft and portable illuminators experience similar environments, and therefore, another source of white light would be highly beneficial to decrease the time and cost associated with replacing lamps therein on a regular interval.

Incandescent lamps can also be easily destroyed by exposure to liquid moisture due to the thermo-mechanical stress associated with contact between the hot glass bulb wall and the room-temperature fluid. Incandescent lamps are also easily damaged by flying stones and the like. Thus, it is very difficult to incorporate an incandescent light on an exterior mirror without going to extreme measures to protect the light bulb from shock, vibration, moisture and flying objects while still allowing for removal of the light fixture when it either burns out or is otherwise permanently damaged.

Incandescent lights also exhibit certain electrical characteristics which make them inherently difficult to incorporate in vehicles, such as an automobile. For instance, when an incandescent light source is first energized by a voltage source, there is an initial surge of

current which flows into the filament. This inrush current, which is typically 12 to 20 times the normal operating current, limits the lifetime of the lamp thus further amplifying the need for an illuminator structure which allows for frequent replacement. Inrush current also necessitates unusual consideration when designing supporting electrical circuits which contain them. Fuses, relays, mechanical or electronic switches, wire harnesses, and connectors electrically connected to such lamps must be capable of repeatedly carrying this extreme transient.

In addition, the voltage-current (V-I) characteristic of incandescent lamps is notoriously non-linear, as is each of the relationships between light output and voltage, current, or power. The luminous intensity, color temperature, and service life of incandescent lamps varies exponentially as a function applied current or voltage. This sensitivity to power source variation makes electronic control of incandescent lamps a particularly difficult problem. They are further susceptible to significant reliability and field service life degradation when subjected continuously to DC electrical power, pulse-width modulated DC power, simple on/off switching of any sort, or any over-voltage conditions, however minor. Incandescent lamps also possess significant inductance which, when combined with their relatively high current load, complicates electronic switching and control greatly due to inductive resonant voltage transients. A typical square wave, DC pulse modulation circuit for a 0.5 amp, 12.8 volt incandescent lamp might produce brief transients as high as 30 volts, for instance, depending on the switching time, the lamp involved, and the inductance, capacitance, and resistance of the remainder of the circuit.

Incandescent lamps also suffer from poor efficiency in converting electrical power into radiated visible white light. Most of the electrical energy they consume is wasted in the form of heat energy while less than 7 percent of the energy they consume is typically radiated as visible light. This has severe negative consequences for vehicular, aerospace, watercraft, and portable illuminator applications where the amount of power available for lighting systems is limited. In these applications, electrical power is provided by batteries which are periodically recharged by a generator on a ship or aircraft, an alternator in an automobile, by solar cells in the case of some remote or aerospace applications, or are otherwise periodically replaced or recharged with an AC/DC adapter such as in the case of a flashlight. Because these mechanisms for restoring battery charge are inherently bulky, heavy, and/or expensive, it is severely detrimental for an illuminator to possess poor power-conversion efficiency in generating visible light. An acute example of the importance in illuminator efficiency is the electric vehicle. For electric bicycles, mopeds, motorcycles, automobiles, golf carts, or passenger or cargo transfer carts, white-light illuminators in the form of electric headlamps, backup lamps, etc. consume an unusually large portion of the vehicle's limited power budget; hence, they would benefit greatest from high-efficiency white-light illuminators. If a more efficient white-light source was available, much less power would be required to energize the illuminator and more power would be available for other systems. Alternatively, the power savings from an improved illuminator would allow for improved power supplies and energy storage or energy replacement mechanisms.

Another result of poor efficiency associated with incandescent lamps is that they generate large amounts of heat for an equivalent amount of generated light as compared to

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other sources. This results in very high bulb-wall temperatures typically in excess of 250°C

and large heat accumulations which must be dissipated properly by radiation, convection, or

conduction to prevent damage or destruction to the illuminator support members, enclosure,

optics or to other nearby vehicle components. This high heat signature of common

5   incandescent light sources in illuminators has a particularly notable impact on the specialized

reflector and lens designs and materials used to collimate and direct the light. Design efforts

to dissipate the heat while retaining optical effectiveness further add requirements for space

and weight to the illuminator assembly, a severe disadvantage for vehicular, watercraft,

aircraft, and portable applications which are inherently sensitive to weight and space

10   requirements.

Portable illuminators such as hand-held flashlights and head-mounted lamps experience

similar problems stemming from incandescent white-light sources and would derive the same

benefits from an improved system.

Physical mechanisms for generating white-light radiation other than incandescence and

15   pyroluminescence are available, including various gas discharges, electroluminescence,

photoluminescence, cathodoluminescence, chemiluminescence and thermoluminescence. The

output of sources using these phenomena can be tailored to meet the requirements of specific

systems; however, they have had limited use in vehicular, watercraft, aircraft or portable

illuminators because of a combination of low intensity, poor efficiency, high voltage

20   requirements, limited environmental resilience, high weight, complexity, high cost, poor

reliability, or short service life.

More recently, great interest has been shown in the use of electroluminescent semiconductor devices such as LEDs as the light source for illuminator systems. Due to their strong coloration and relatively low luminous output as compared to incandescent lamps, early generations of LEDs found most of their utility as display devices, *e.g.*, on/off and matrix-addressed indicators, etc. These uses still dominate the LED market today, however, recent advances in LED materials, design, and manufacturing have resulted in significant increases in LED luminous efficacy and, in their most recent commercial forms, exhibit a higher luminous efficacy than incandescent lights. But, even the latest LEDs emit highly saturated, narrow-bandwidth, distinctively non-white light of various hues. As discussed above, white light in one of its various manifestations is essential for most illuminator systems.

Despite the inherent colorfulness of LEDs, they offer many potential advantages as compared to other conventional low-voltage light sources for vehicles, watercraft, aircraft, and portable illuminators. LEDs are highly shock resistant and therefore provide significant advantages over incandescent and fluorescent bulbs which can shatter when subjected to mechanical or thermal shock. LEDs possess operating lifetimes from 200,000 hours to 1,000,000 hours, as compared to the typical 1,000 to 2,000 hours for incandescent lamps or 5,000 to 10,000 hours for fluorescent lamps.

It has been known that the narrow-band spectral emissions of several saturated light sources having different apparent colors can be combined to produce an additive color mixture having an apparent color which is different than that of any of its constituents. The basics of additive color are evident, for instance, in the observation that white sunlight decomposes into its constituent spectra when refracted by a prism or dispersions of water droplets such as

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occurs in a typical rainbow. The visible white light of the sun can therefore be considered an additive color mixture of all of the hues associated with its radiation in the visible spectrum having wavelengths from 380 to 780 nanometers.

An important and common example of additive color mixtures is the technique used in most color display screens possessing a cathode ray tube (CRT) or a liquid crystal display (LCD) element. These displays consist of addressable arrays of pixels, each of which contains sub-pixels having the hues red, green, and blue which can be energized alone or in combinations. In the case of the CRT, each sub-pixel is a dot of inorganic phosphor which can be excited via cathodoluminescence by a steered electron beam. In the case of the LCD, each sub-pixel is a dot of colored dye in registry with a switchable liquid crystal shutter, the combination of which acts as a reconfigurable filter for a backlight. The result in either of these cases is that a brightly colored red sub-pixel can be energized simultaneously with an adjacent bright green pixel in unresolvable proximity to the red in order to form the perceived color yellow. A similar combination of the green sub-pixel and a blue one will form the perceived color cyan. A similar combination of the red sub-pixel and a blue one will form the perceived color magenta. Energizing all three of the red, green, and blue sub-pixels within a pixel concurrently will yield the perceived color white, if the brightness of each sub-pixel is proportioned properly. The relative proportions of the brightness of each of these differently colored sub-pixels can further be actively manipulated in a wide variety of combinations resulting in a continuum of perceived colors nearly replicating all of the colors available within human color vision, including white. Unfortunately, while these types of displays may exhibit appreciable surface brightness, they are extremely bulky, expensive and complicated and do

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not project suitable amounts of illumination at a distance to be of use as effective illuminators.

For example, even the brightest and largest television screen casts only a dim glow across a

darkened room. The illumination level associated with this dim glow is barely sufficient for

reading a newspaper and is completely inadequate to identify objects or colors in a detailed

photograph. However, the capability of such an R-G-B display system to reproduce

appreciably all of the colors available within human color vision is an excellent example of the

important phenomenon known as metamerism, which will be discussed in greater detail

hereinafter.

LEDs are available in various hues and it is known that the output of red, blue, and

green LEDs can be combined in a fashion similar to that used for a CRT in the proper

proportions to produce a variety of perceived colors, including the perceived color white. For

example, U.S. Patent No. 5,136,483 issued to Karl-Heinz Schoniger et al. discloses a light

emitting device having twelve LEDs arranged to form a headlamp or signaling lamp.

Schoniger et al. also discloses that to produce white light, red, green, and blue LEDs need to

be used simultaneously. However, such a system is rather complicated, and Schoniger et al.

does not mention the inherent susceptibility of an R-G-B system to unacceptable variation due

to significant variations in luminous output produced from one LED to another of the same

type. Such LED variations cause errors in the relative proportions of the actual color mixture

produced versus that desired and, coupled with high complexity and cost, render the system

undesirable for most practical uses.

Consequently, it is desirable to provide a highly reliable, low-voltage, long-lived, LED

illuminator capable of producing white light with sufficient luminous intensity to illuminate

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subjects of interest well enough to be seen and to have sufficient apparent color and contrast so as to be readily identifiable.

SUMMARY OF THE INVENTION

Accordingly, a primary aspect of the present invention is to provide a light emitting assembly projecting effective white light and having a plurality of light sources of two types whose visible emissions have hues which are complementary to one another and combine to form a metameric white light.

Another aspect of the present invention is to provide a high efficiency light emitting assembly, for use in limited power applications, projecting effective white light and having a plurality of light sources of two types whose visible emissions have hues which are complementary to one another and additively combine to form light with a metameric white color.

Yet another aspect of the present invention is to provide a light emitting assembly projecting an effective photopic white light within a central zone and mesopic illumination in a surrounding zone bounded from the first by a photopic illuminance threshold and having a plurality of light sources of two groups or types whose emissions form an additive binary complementary or equivalent binary complementary color mixture.

To achieve these and other aspects and advantages, a light emitting assembly of the present invention comprises a first light source and a second light source. The first and second light sources are oriented such that when the first and second light sources emit light, light projected from the first and second light sources overlaps and is capable of forming effective white light. The light projected from the first source exhibits color coordinates

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different from the light projected from the second light source. The first light source is preferably a solid state light source. Preferably, neither of the first and second light sources projects light having a red hue. The second light source may be a photoluminescent source that is disposed to receive light from the first light source. The photoluminescent source may be disposed on or within an encapsulant formed over the first light source, disposed directly over the first light source, or disposed on or within an optical element spaced apart from the first light source. The optical element may be a lens and/or a diffuser.

These and other features, advantages, and objects of the present invention will be further understood and appreciated by those skilled in the art by reference to the following specification, claims, and appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the concluding portion of the specification. The invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, where like numerals represent like components, in which:

Fig. 1 is a cross-sectional view of an illuminator assembly according to the present invention incorporating conventional discrete LEDs;

Fig. 2 is a cross-sectional view of an illuminator assembly according to the present invention incorporating a plurality of LED chips in a chip-on-board configuration;

Fig. 3 is a graph plotting the relative spectral power versus wavelength for Standard Illuminants A, B, and C, as well as amber and blue-green LEDs;

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Figs. 4a, 4b, and 4c are a series of graphs plotting the relative spectral power versus wavelength for amber and blue-green LEDs, the spectral reflectance versus wavelength for a 50 percent neutral gray target, and the relative spectral power versus wavelength for the resultant reflected light, respectively;

Fig. 5 is a graph plotting the relative sensitivity of a standard two-degree observer versus wavelength for photopic vision, scotopic vision as well as an estimated mesopic vision;

Fig. 6 is a graph plotting the relative response of the color-matching functions for a standard two-degree observer versus wavelength during photopic vision;

Fig. 7 is a CIE 1976 uniform chromaticity scale (UCS) diagram showing the location of the Planckian Locus, the location of the translated SAE J578 boundaries for achromatic white light, the locations of CIE Standard Illuminants A, B, and C as well as the locus of binary additive mixtures from blue and red LEDs;

Fig. 8 is a CIE 1976 UCS diagram showing the location of the Planckian Locus, the locations of Standard Illuminants A, B, and C, the location of the translated SAE J578 boundaries for achromatic white light, the locus of ternary additive mixtures from red, green, and blue LEDs, as well as an estimated locus of red, green, and blue LED manufacturing variation;

Fig. 9 is a CIE 1976 UCS diagram showing the location of the Planckian Locus, the locations of Standard Illuminants A, B, and C, the location of the translated SAE J578 boundaries for achromatic white light, and the approximate location of the white color boundary translated from the revised Kelly chart, as well as the locus of binary additive mixtures from deep red and deep green LEDs;

Fig. 10 is a CIE 1976 UCS diagram showing the location of the Planckian Locus, the locations of Standard Illuminants A, B and C, the location of the translated SAE J578 boundaries for achromatic white light, and the locus of binary additive mixtures from amber 592 nm and blue-green 488 nm LEDs which is substantially coaxial with the Planckian Locus;

Fig. 11 is a CIE 1976 UCS diagram showing the location of the Planckian Locus, the locations of Standard Illuminants A, B and C, the location of the translated SAE J578 boundaries for achromatic white light, the approximate location of the white color boundary translated from the revised Kelly chart, and the locus of binary additive mixtures from a range of amber and blue-green LEDs which is substantially coaxial with the Planckian Locus;

Fig. 12 is a CIE 1976 UCS diagram showing the location of the Planckian Locus, the locations of Standard Illuminants A, B, and C, the location of the translated SAE J578 boundaries for achromatic white light, and the locus of binary additive mixtures from amber 584 nm and blue-green 483 nm LEDs which is substantially coaxial with the Planckian Locus;

Fig. 13 is a CIE 1976 UCS diagram showing the locations of Standard Illuminants A, B, and C, the location of the translated SAE J578 boundaries for achromatic white light, and the locus of binary additive mixtures from equivalent 584 nm amber and equivalent 483 nm blue-green LEDs which is substantially coaxial with the Planckian Locus;

Figs. 14a is a perspective view of an automotive interior rearview mirror incorporating the illuminator assembly of the present invention, and Figs. 14b and 14c are cross-sectional views of exemplary mirror elements for insertion into the rearview mirror;

Fig. 15 is an illustration of a specification for an area targeted by illumination from an automotive interior rearview mirror maplight;

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Fig. 16 is an illustrative illumination pattern for an illuminator assembly according to the present invention;

Fig. 17 is a perspective three-dimensional chart plotting the intensity distribution from an illuminator maplight according to the present invention borne by an automotive interior electrochromic mirror;

Fig. 18 is an iso-intensity contour chart plotting the intensity distribution from an illuminator maplight according to the present invention borne by an automotive interior electrochromic mirror;

Fig. 19 is an iso-illuminance contour chart plotting the illumination pattern at a target from an illuminator maplight according to the present invention borne by an automotive interior electrochromic mirror;

Fig. 20 is a contour map plotting the surface luminance of a 50 percent neutral gray target illuminated by an illuminator maplight according to the present invention borne by an automotive interior rearview mirror;

Fig. 21 is a schematic diagram of an electronic circuit operable to power the illuminator assembly of the present invention;

Fig. 22 is a plot of the specified maximum forward current versus temperature for a typical LED and the experimentally determined forward current versus temperature plot for the LEDs of the present invention operated by the circuit of Fig. 21, as well as the design current versus temperature plot for the LEDs of the present invention operated by the circuit of Fig. 21 which also incorporates microprocessor software controls;

Fig. 23a is an isometric view of a semiconductor optical radiation emitter package without an encapsulant and prior to singulation;

Fig. 23b is an isometric view of an encapsulated and singulated semiconductor optical radiation emitter package according to an embodiment of the present invention;

Figs. 24a and 24b are schematic diagrams of various emitter electrical configurations;

Fig. 25 is an isometric view of an alternate embodiment of a semiconductor optical radiation emitter device of the present invention;

Figs. 26a and 26b are isometric views of an alternate embodiment of a semiconductor optical radiation emitter device with and without encapsulation;

Figs. 27a and 27b are isometric views of yet another alternate embodiment of a semiconductor optical radiation emitter device with and without encapsulation;

Fig. 28 is a cross-sectional view of a light emitting assembly constructed in accordance with another embodiment of the present invention;

Fig. 29 is an elevational side view of a light emitting assembly constructed in accordance with yet another embodiment of the present invention;

Fig. 30 is a graph plotting the relative spectral power versus wavelength for amber and blue-green light sources constituting an examplary binary complementary pair; and

Figs. 31A and 31B are a pair of graphs plotting the relative spectral power versus wavelength for amber and blue-green light sources and an amber photoluminescent source individually and as a sum, respectively.

DETAILED DESCRIPTION OF THE INVENTION

The present invention generally relates to an improved light assembly and more specifically to a white-light emitting assembly for use in limited power applications such as vehicles, portable lamps, and specialty lighting. By vehicles, we mean over-land vehicles, watercraft, aircraft and manned spacecraft, including but not limited to automobiles, trucks, vans, buses, recreational vehicles (RVs), bicycles, motorcycles and mopeds, motorized carts, electric cars, electric carts, electric bicycles, ships, boats, hovercraft, submarines, airplanes, helicopters, space stations, shuttlecraft and the like. By portable lamps, we mean camping lanterns, head or helmet-mounted lamps such as for mining, mountaineering, and spelunking, hand-held flashlights and the like. By specialty lighting we mean emergency lighting activated during power failures, fires or smoke accumulations in buildings, microscope stage illuminators, billboard front-lighting, backlighting for signs, etc. The light emitting assembly of the present invention may be used as either an illuminator or an indicator. Examples of some of the applications in which the present invention may be utilized, are disclosed in commonly assigned U.S. Patent Application No. 09/425,792 entitled "INDICATORS AND ILLUMINATORS USING A SEMICONDUCTOR RADIATION EMITTER PACKAGE," filed on October 29, 2000, by J. Roberts et al., the entire disclosure of which is incorporated herein by reference.

The present invention provides a highly reliable, low-voltage, long-lived, light sources for vehicles, portable lighting, and specialty lighting capable of producing white light with sufficient luminous intensity to illuminate subjects of interest well enough to be seen and to have sufficient apparent color and contrast so as to be readily identifiable. The light

assemblies of the present invention exhibit extremely predictable electronic properties and are well suited for use with DC power sources, pulse-width modulated DC power sources, and electronic control systems.

As used herein, the terms "light emitting sources" and "light sources" shall include any structure that generates and emits radiation, preferably visible light. Such light sources may include electroluminescent sources or other solid-state sources and/or photoluminescent sources. One form of electroluminescent source includes semiconductor optical radiation emitters. For purposes of the present invention, semiconductor optical radiation emitters 202 comprise any component or material that emits electromagnetic radiation having a wavelength between 100 nm and 2000 nm by the physical mechanism of electroluminescence, upon passage of electrical current through the component or material. The principle function of a semiconductor optical emitter 202 within the present invention is the conversion of conducted electrical power to radiated optical power. A semiconductor optical radiation emitter 202 may include a typical infrared, visible or ultra-violet LED chip or die well known in the art and used in a wide variety of prior art devices.

Alternate forms of semiconductor optical emitters which may be used in the present invention are light emitting polymers (LEPs), polymer light emitting diodes (PLEDs), organic light emitting diodes (OLEDs), and the like. Such materials and optoelectronic structures made from them are electrically similar to traditional inorganic LEDs, but rely on organic compositions such as derivatives of the conductive polymer polyaniline for electroluminescence. Such semiconductor optical emitters are relatively new, but may be

obtained from sources such as Cambridge Display Technology, Ltd. of Cambridge, and from Uniax of Santa Barbara, California.

For brevity, the term semiconductor optical radiation emitter may be substituted with the term LED or the alternate forms of emitters described above or known in the art.

5 Examples of emitters suitable for the present invention include varieties of LED chips with associated conductive vias and pads for electrical attachment and that are emissive principally at P-N junctions within doped inorganic compounds of AlGaAs, AlInGaP, GaAs, GaP, InGaN, GaN, SiC, and the like.

LEDs are a preferred electroluminescent light source for use in the light emitting assemblies of the present invention because LEDs do not suffer appreciable reliability or field-service life degradation when mechanically or electronically switched on and off for millions of cycles. The luminous intensity and illuminance from LEDs closely approximates a linear response function with respect to applied electrical current over a broad range of conditions, making control of their intensity a relatively simple matter. Finally, recent generations of AlInGaP, AlGaAs, and GaN LEDs draw less electrical power per lumen or candela of visible light produced than incandescent lamps, resulting in more cost-effective, compact, and lightweight illuminator wiring harnesses, fuses, connectors, batteries, generators, alternators, switches, electronic controls, and optics. A number of examples have previously been mentioned and are incorporated within the scope of the present invention, although it should be recognized that the present invention has obvious other applications beyond the specific ones mentioned which do not deviate appreciably from the teachings herein and therefore are included in the scope of this invention.

Another preferred light source that may be used in the inventive light emitting assembly is a photoluminescent source. Photoluminescent sources produce visible light by partially absorbing visible or invisible radiation and re-emitting visible radiation. Photoluminescent sources include fluorescent dyes, pigments, and crystals, as well as phosphors. Such a fluorescent or phosphorescent material may be excited by an LED and may be disposed within or on the LED, or within or on a separate optical element, such as a lens or diffuser that is not integral with an LED. Exemplary structures using a fluorescent or phosphorescent light source are described further below.

Figs. 1 and 2 show two embodiments of the present invention using LEDs of two substantially different configurations. Fig. 1 shows an embodiment incorporating conventional discrete LEDs, and Fig. 2 shows an embodiment incorporating individual LED chips.

Conventional discrete LED components include such LED devices such as T 1, T 1-3/4, T 5, surface mount (SMD), axial-leaded "polyleds," and high power packages such as the SuperNova, Pirahna, or Brewster lamps, all of which are available with a variety of options known to those skilled in the art such as color, size, beam width, etc. Appropriate conventional discrete LEDs may be obtained from manufacturers such as Hewlett Packard, Inc.; Optoelectronics Division, located in San Jose, California; Stanley Electric Company, LTD located in Tokyo, Japan; Nichia Chemical Industries, LTD located in Anan-shi, Tokushima-ken, Japan, and many others.

Conventional discrete LEDs 14 are the dominant form of LEDs in general use because of their generic shapes and ease of processing in standard printed circuit board assembly operations. Referring to Fig. 1, a light emitting assembly 10 is shown including a support

member 12 that supports, delivers electrical power to, and maintains a spatial relationship between a plurality of conventional discrete LEDs 14. The structure of support member 12 will vary depending on the specific design of the LEDs 14 and of assembly 10, and may be a conventional printed circuit board or optionally may be a portion of housing 19 into which the

5   light emitting assembly 10 is being incorporated. Support member 12 may be shaped such that the emission of all of the LEDs is aligned or otherwise focused on a common spot at some predetermined distance away from assembly 10. A conventional discrete LED 14 generally consists of a pre-assembled or packaged "lamp," each of which normally includes a metal lead frame 17 or other substrate for electrical and mechanical connection and internal mechanical

10   support, a semiconductor LED chip or "die" 16, a conductive adhesive or "die attach" (not shown) for electrically and mechanically attaching one electrode of the chip 16 to the lead frame 17 or other substrate, a fine wire conductor 20 for electrically connecting the other electrode of the chip 16 to an area of the lead frame 17 or other substrate which is electrically isolated from the first electrode and die attach by the chip 16 itself. Optionally, a miniature

15   reflector cup (not shown) may also be located adjacent to the chip 16 to further improve light extraction from the device. Finally, a clear, tinted, or slightly diffused polymer matrix enclosure 18 is used to suspend, encapsulate, and protect the chip 16, lead frame 17, optional reflector cup (not shown), and wire conductor 20 and to provide certain desirable optical characteristics.

20   In conventional discrete LEDs 14, the polymer matrix enclosure 18 typically comprises an optically clear epoxy or any number of materials capable of protecting the LED chip 16 and an upper portion of lead frame 17 from environmental contaminants such as moisture. As

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shown in Fig. 1, polymer matrix enclosure 18 can further be made integral with lens 27 which

will be discussed in greater detail hereinbelow. The upper portion of lead frame 17 is

connected to the LED semiconductor chip 16 and a lower portion of lead frame 17 extends out

one end of the enclosure 18 to attach to support member 12 and provide electrical connection

5   to an electronic control circuit 22 through wires 23. Circuit 22 is operable to energize,

control, and protect the LEDs 14, and manipulate and manage the illumination they produce.

Many variations of electronic control circuit 22 will be known to those skilled in the art and

will vary depending on the application for assembly 10. For example, electronic control

circuit 22 for a flashlight may simply be an ON-OFF switch, a battery and a resistor in series

10 with the LEDs 14 and support member 12. However, for an automotive rearview mirror

assembly, described in detail hereinbelow, circuit 22 will be slightly more complex.

In most conventional discrete LED designs, enclosure 18 also acts as an integral optical

element such as a lens 27, deviator 28, or diffuser 29; however, separate or secondary optical

elements 21 are preferably incorporated in light emitting assembly 10 to improve illuminator

15 performance or appearance. Furthermore, as described below with respect to Figs. 23-27,

more than one individual LED chip 16 of the same color or of different colors may be

incorporated within a single polymer matrix enclosure 18 such that the spacing between

conventional discrete LEDs 14 is greater than the spacing between individual chips 16.

A second configuration of LEDs is the individual LED chip, consisting solely of a

20 semiconductor LED chip (without a pre-attached lead frame, encapsulating media, conducting

wire, etc.). These are generally shipped in vials or adhered to a membrane called "sticky

back" and are mounted in an intermediate manufacturing step directly onto a printed circuit

board, ceramic substrate, or other structure to support the individual LED chip and provide

electrical connections to it. When a plurality of LEDs is so mounted, the result is a "chip-on-

board" LED array that in its entirety can then be incorporated into other assemblies as a

subcomponent. Individual LED chips suitable for the present invention are available from

5   Hewlett Packard, Showa Denko, Stanley, and Cree Research, to name just a few. Referring to

Fig. 2, if chip-on-board LED designs are utilized, then light illuminating assembly 10 has a

support member 12 which may be a printed circuit board, ceramic substrate, housing or other

structure capable of supporting the individual LED chips 16 while simultaneously providing

electrical connection for powering the chips 16. In this configuration, individual LED chips

10   16 are placed on support member 12, thereby eliminating the bulky pre-packaged polymer

matrix enclosure 18, and lead frame 17 of the conventional discrete type of LED 14 in Fig. 1.

A more integrated and optimized system is therefore possible by virtue of the flexibility to

place individual LED chips 16 within very close proximity to one another on the support

member 12 and within very close proximity to reflector 26, lens 27, and/or secondary optical

15   elements 21 used to enhance the light emissions of LED chip 16. In this manner, one or more

LED chips 16 can be placed at or very near the focus of a single lens 27 or lenslet 27a (as

shown in areas A and B), improving the alignment and uniformity of the resultant mixed beam

projected therefrom. Individual LED chips 16 are very small (on the order of 0.008 inches x

0.008 inches x 0.008 inches) and can be placed very closely to one another by precision

20   equipment, e.g., pick-and-place machines. Such close pitch spacing is not possible with the

conventional discrete LEDs 14 of Fig. 1 because of their relatively large size and larger

tolerances associated with their manufacture and assembly. Furthermore, the ability to tightly

pack the chips 16 allows extreme design flexibility, improving the aesthetic appeal of assembly 10.

For chip-on-board designs, the individual LED chips 16 are electrically connected to conductive pad 24 by a fine conductive wire 20 and attached to conductive pad 25 by an

5 electrically conductive die attach adhesive (not shown). The chips 16 and conductive pads 24 and 25 are mounted on, and held in a spaced-apart relationship from one another, by support member 12. LED chips 16 are electrically connected to the support member 12, and to electronic circuit 22, through pads 24 and 25, support member 12 and wires 23.

Referring to Areas A and B, the number, spacing, color, and pattern of individual LED

10 chips 16 under each lenslet 27a can vary from system to system. One or more chips 16 of the same color or different colors chosen according to the teachings of this invention may be placed under a single lenslet 27a such that the spacing between groups of LED chips is greater than the spacing between individual chips. For instance, in Area A, two of the three individual LED chips 16 shown may be a type that emits amber light when energized and the

15 third may be of a type which emits blue-green light when energized. Alternatively, two may be of the blue-green variety and one may be of the amber variety. Also, it is possible for all of the LEDs in Area A to be of one color, e.g., amber, if another nearby group in the plurality of the assembly such as that shown in Area B of Fig. 2 contains an appropriate number of complementary LEDs, e.g., two of the blue-green variety.

20 A reflector 26 may optionally be used with the above-described conventional discrete LED designs as shown in Fig. 1 or with LED array chip-on-board designs shown in Fig. 2. The reflector 26, if used, is normally a conical, parabolic, or elliptical reflector and typically

is made of metal or metal-coated molded plastic. The purpose of the reflector 26 is to collect

or assist in the collection of light emitted by the LED chip 16 and project it toward the area to

be illuminated in a narrower and more intense beam than otherwise would occur. For chip-on-

board LED array designs, reflector 26 is commonly a planar reflector made integral with

5   conductive pad 25 by selective plating of a reflective metal (such as tin solder) and is oriented

radially around the LED chip 16. In this case, of course then the combined

reflector/conductive pad serves the previously described functions of both the reflector 26 and

the conductive pad 25. Suitable reflectors 26 are well known to those skilled in the art and

may be obtained from a wide variety of optical molding and coating companies such as Reed

10   Precision Microstructures of Santa Rosa, California. More than one reflector 26 to be used

for conventional LEDs 14 or LED chips 16 can be combined to make a reflector array whose

constituent elements are oriented in substantial registry with the conventional LEDs 14 or LED

chips 16.

As shown in Fig. 1 and Fig. 2, lens 27 is normally a magnifier/collimator which serves

15   to collect light emitted by each conventional LED 14 or LED chip 16 and reflected by optional

reflector 26 and projected in a narrower and more intense beam than otherwise would occur.

As shown in Fig. 1 for a light emitting assembly 10 using conventional LEDs 14, lens 27 is

commonly made integral with polymer matrix enclosure 18, or otherwise may be made

separately from polymer matrix enclosure 18. Lens 27 may also be made as an integral array

20   of lenslets 27a which are then substantially registered about the centers of individual

conventional discrete LEDs 14.

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As shown in Fig. 2 for a light emitting assembly 10 using individual LED chips 16 in a chip-on-board configuration, more than one lenslet 27a can be combined in an array to make lens 27 whose constituent elements are lenslets 27a oriented in substantial registry with the LED chips 16, reflectors 26, and pads 24 and 25. In Fig. 2, lenslets 27a are shown as total

5 internal reflection (TIR) collimating lenses whose concave surfaces (facing the individual LED chips 16) consist of radial microprism structures similar to those on a Fresnel lens. However, it should be understood that plano-convex, bi-convex, aspheric or their Fresnel, total-internal-reflection (TIR), catadioptric or holographic optic element (HOE) equivalents are typical variants of lenslet 27a. Lens 27 or lenslets 27a are used with a wide variety of options known

10 to those skilled in the art such as color, f-number, aperture size, etc. These may be obtained from various manufacturers including U.S. Precision Lens, Reed Precision Microstructures, 3M, Fresnel Optics Company, and Polaroid Corporation.

Referring simultaneously to Figs. 1 and 2, one or more optional secondary optical elements 21 are used with the above-described conventional discrete LED designs (Fig. 1) or

15 with LED array die-on-board designs (Fig. 2). Secondary optical elements 21 are components that influence by combination of refraction, reflection, scattering, interference, absorption, and diffraction the projected beam shape or pattern, intensity distribution, spectral distribution, orientation, divergence and other properties of the light generated by the LEDs. Secondary optical elements 21 comprise one or more of a lens 27, a deviator 28, and a diffuser 29, each

20 of which may be in conventional form or otherwise in the form of a micro-groove Fresnel equivalent, a HOE, binary optic or TIR equivalent, or another hybrid form.

A deviator 28 may be optionally mounted on or attached to the housing 19 or otherwise attached to or made integral with the lens surface 27b and used to conveniently steer the collimated beam in a direction oblique to the optic axis of the lens 27 and/or reflector 26 used in the light emitting assembly 10. Deviator 28 is normally a molded clear polycarbonate or

5 acrylic prism operating in refractive mode for deviation angles up to about 35° or in TIR mode (such as a periscope prism) for deviation angles in excess of 35°. This prism may further be designed and manufactured in a micro-grooved form such as a Fresnel equivalent or a TIR equivalent. Furthermore, a diffraction grating, binary optic, or holographic optical element can be substituted for this prism to act as a deviator 28. In any of these cases, the deviator 28

10 is configured as a sheet or slab to substantially cover the entire opening of the illuminator housing 19 from which light is emitted. Such deviators are available from the same sources as the lens manufacturers listed above.

Optionally, a diffuser 29 may be mounted on or attached to the housing 19 or otherwise attached to or made integral with the lens surface 27b or the deviator surface 28a and is used

15 to aesthetically hide and physically protect the illuminator internal components, and/or to filter the spectral composition of the resultant illuminator beam, and/or narrow, broaden or smooth the beam's intensity distribution. This can be helpful, for instance, in improving color and brightness uniformity of the effective illumination projected by the illuminator. Alternatively, diffuser 29 may include unique spatial filter or directional film such as light control film

20 (LCF) from 3M to sharpen the beam cut-off properties of assembly 10. The diffuser 29 may further incorporate a unique spectral filter (such as a tinted compound or an optical coating such as dichroic or band pass filter) to enhance aesthetics, hide internal components from

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external view, or correct the color of mixed light projected by assembly 10. Diffuser 29 is normally a compression or injection molded clear polycarbonate or acrylic sheet whose embossed surface or internal structure or composition modifies impinging light by refraction, reflection, total internal reflection, scattering, diffraction, absorption or interference. Suitable

5   holographic diffusers 29 can be obtained from Physical Optics Corporation in Southern California, and binary optics may be obtained from Teledyne-Brown of Huntsville, Alabama.

It is preferred to have as few optical members as practical and, therefore, at least two can be combined into one integral piece. For example, deviator 28 can be incorporated onto an upper surface 27b of lens 27 by simply placing an appropriately machined mold insert into

10   the planar half of a mold for a Fresnel or TIR collimator lens. As mentioned hereinabove and shown in Fig. 2, diffuser 29 may also be attached to or made integral with the lens surface 27b or the deviator surface 28a. Procedures for consolidating the optical members will be known to those skilled in the art as will substituting various individual types of optical members for those listed above. All such combinations are intended to be within the scope of the present

15   invention. Clearly, whether conventional discrete LEDs 14 or individual chips 16 are used, those skilled in the art will understand that many modifications may be made in the design of support member 12 while still staying within the scope of the present invention, and all such modifications should be understood to be a part of the present invention.

According to other embodiments of the present invention, a light emitting assembly of

20   the present invention may include a high-power multi-chip LED device as disclosed in International PCT Application No. PCT/US00/07269, the entire disclosure of which is

incorporated herein by reference. Examples of the structures taught in PCT/US00/07269 are shown in Figs. 23-27 and described below.

Referring to Figs. 23a and 23b, a light emitting assembly 200 according to another embodiment of the present invention contains three major components: a leadframe 201, at least one semiconductor optical radiation emitter 202, and an encapsulant 203. Leadframe 201 serves as a support for mounting a semiconductor optical radiation emitter 202, such as an LED chip, provides a mechanism for electrical connection to the semiconductor optical radiation emitter 202, and provides thermal paths for removing heat generated within the semiconductor optical radiation emitter 202 during operation and transferring this heat to adjacent media, adjacent structures or the surrounding environment. The leadframe includes two primary elements: a heat extraction member 204 and a plurality of electrical leads, indicated collectively by 205.

The heat extraction member 204 consists of a thermally conductive body, typically composed of metal but potentially composed of a thermally conductive ceramic or other material that provides a dominant path (distinct from the leads 205) to transfer heat generated by the emitter of the device into the ambient environment. Preferably, the heat extraction member 204 functions to transfer more of the heat generated by the emitter out of the device into the ambient environment than is transferred by the electrical leads 205. Preferably, the heat extraction member 204 is constructed to transfer more than 75 to 90 percent of this power out of the device into the ambient environment, adjacent structures or surrounding media. Heat extraction member 204 transfers heat out of the encapsulation 203 to the ambient environment via a path having a location separate from the points of entry into the

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encapsulation of the electrical leads 205. Thus, the heat extraction member 204 forms the dominant thermal conduit to and from the semiconductor optical emitter 202 within the device 200, a conduit that is substantially independent of the electrical conduits to and from the device.

Broadly speaking, the heat extraction member 204 may range in thickness from 0.25 mm to 5.0 mm, in width (dimension 207) from 2 mm to 25 mm, and in length (dimension 208) from 2 mm to 25 mm. Preferably, the heat extraction member 204 is a modified rectangular solid approximately 1.0 to 2.0 mm thick, 9.5 to 12.0 mm wide (dimension 207) and 10.0 to 17.0 mm long (dimension 208). In another more preferred embodiment, the heat extraction member 204 is a modified rectangular solid approximately 1.625 mm thick, 11.0 mm wide (dimension 107) and 12.5 mm long (dimension 208). These dimensions ensure compatibility with standard auto-insertion equipment and standard mounting and heat-sink components. These ranges of dimensions yield a heat extraction member with a large cross-sectional area conducive to heat extraction.

As discussed in greater detail below, the heat extraction member 204 may be constructed with a generally elliptical, circular or other non-rectangular form, and may be chamfered, or otherwise contain extensions, slots, holes, grooves and the like, and may incorporate depressions such as a collimating cup or other form to enhance optical performance. The heat extraction member 204 may be composed of copper, copper alloys such as beryllium copper, aluminum, steel, or other metal, or alternatively of another high thermal conductivity material such as ceramic. Suitable leadframe materials are available from a wide variety of sheet metal companies including Olin Brass of East Alton, Illinois.

The heat extraction member 204 provides a primary path out of the package for heat

generated by the semiconductor optical radiation emitter 202 to the ambient environment or to

structures or media adjacent the package 200. To accomplish this, the heat extraction member

204 must exhibit a low thermal resistance between the surface region where it is attached to

5   the semiconductor optical emitter 202 and the ambient environment or adjacent structures.

The heat extraction member 204 accomplishes low thermal resistance to ambient or adjacent

structures by a combination of one or more of the following attributes: 1) construction with

substantially high thermal conductivity material such as copper, copper alloys such as

beryllium copper, aluminum, soft steel, or other metal, or alternatively of another high

10   thermal conductivity material such as ceramic; 2) construction with a substantially high cross-

sectional area in one or more directions leading away from the surface region where the

semiconductor optical emitter is attached; 3) construction with a relatively short path length in

one or more direction from the surface region where the semiconductor optical emitter is

attached to the ambient environment or adjacent structures; 4) construction with structural

15   details such as fins or perforations or other features yielding a high surface area exposed to

air, surrounding media or adjacent structures (outside the device encapsulant) relative to device

power to enhance convective and radiative heat loss; and 5) treatment of surfaces exposed to

air, surrounding media or adjacent structures (outside the device encapsulant) with textures or

coating materials having improved emissivity such as nichrome, black-oxide or matte finish to

20   enhance radiative heat loss by emission.

Another function of the heat extraction member 204 in some embodiments of the

present invention is to dampen the effects of transient thermal exposure experienced by the

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device during soldering of the electrical leads 205. The heat extraction member 204 can accomplish this directly and indirectly. Direct dampening by the heat extraction member 204 of temperature extremes from soldering of electrical leads 205 is accomplished in embodiments of the present invention where the heat extraction member 204 is connected to or made

5   integral with the one or more of the electrical leads 205 being soldered. Since the heat extraction member 204 is constructed with materials and geometry giving it a substantially high heat capacity, and the solderable electrical leads 205 are constructed with a relatively high thermal resistance between their standoff seating plane and the heat extraction member 204, temperature excursions caused by heat traveling up the electrical leads 205 during

10   soldering are dampened. This function is analogous to that of an electrical "RC" filter for dampening voltage transients in an electrical circuit.

Indirect dampening of temperature extremes from soldering of electrical leads 205 is accomplished by the heat extraction member 204 by providing a dominant low thermal resistance path out of the device 200 which is substantially independent of the thermal path

15   represented by the electrical leads. This allows the electrical leads 205 to be constructed with relatively high thermal resistance without compromising LED operational performance. Such a compromise exists in solderable prior art devices that rely on their electrical leads for supplying electrical current and for heat extraction. In the present invention, since the electrical leads 205 may be constructed with arbitrarily high thermal resistance without regard

20   to their thermal impact during operation, the device can be very effectively protected against thermal transients travelling up the electrical leads 205 during soldering. Their high thermal resistance reduces the temperature extreme that would otherwise be reached within the device

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encapsulant 203 at and beyond the points where the electrical leads 205 enter the encapsulant 203. Additional functions of the heat extraction 204 member may include: 1) means of mechanically gripping or placing the device; 2) means for attaching or registering to adjacent components such as secondary optics, support members or secondary heat extractors; 3) partial optical collimation or other beam reformation of energy emitted by the semiconductor optical emitter; and 4) partial mixing of energy emitted by a plurality of semiconductor optical emitters if a plurality is present.

To support these additional functions, additional characteristics may be required of the heat extraction member 204, some of which are illustrated in Fig. 23A. Slots 230, through-holes 232, tabs 234 or standoffs (not shown) may be stamped directly into the metal of the heat extraction member 204 to facilitate handling by automated handling and placement in processing by mechanical grippers. Similar structural details may be incorporated for attachment of the device of the present invention to adjacent components. By attachment to a heat sink, housing or other adjacent component or material, thermal extraction from the device may be further improved. Using similar features, secondary optical components may be readily snapped-to or registered against devices of the present invention for superior optical performance and minimized variance.

By stamping a depression or cup 301 into the heat extraction member 204 and subsequently mounting semiconductor optical emitters 202 within this recess, the depressed surface of the heat extraction member 204 may serve as an optical collector and reflector, thereby improving optical performance of the device. The surface of the heat extraction member 204 surrounding the semiconductor optical emitter 202, including surfaces of an

optical cup or depression 301 if present, may be coated with a highly reflective coating such as silver, aluminum, gold, etc. to enhance optical efficiency. Such stamping and coating features can also provide a narrower and more powerful beam and or provide a more evenly distributed beam. The surface of the heat extraction member 204 surrounding the semiconductor optical

5 emitter 202, including surfaces of an optical cup or depression 301 if present, may additionally or alternately be coated or textured so as to increase diffuse reflectance or scattering. In devices which contain more than one semiconductor optical radiation emitter 202, these treatments can also improve the mixing of energy within the beam resulting from the combined emissions of the plurality of emitters contained therein.

10 In a preferred embodiment of the present invention, one or more electrical leads 209 is made as a narrow integral extension of the heat extraction member 204. This is illustrated by the direct physical connection between lead 209 and heat extraction member 204. This physical connection 206 may occur either within the perimeter of the encapsulant 203 or exterior to the encapsulant. In this fashion, the integral electrical lead 209 is electrically

15 continuous with the heat extraction member 204 such that electrical current may be delivered through a short portion of the heat extraction member 204 from the integral electrical lead 209 to contact at the base surface of the semiconductor optical radiation emitter 202. The remaining one or more isolated electrical leads 210 is not connected to heat extraction member.

20 If one of the electrical leads 205 of an embodiment is an integral electrical lead 209, and the semiconductor radiation emitter 202 is of the type including an electrical contact at its base, then the polarity of this lead 209 is typically configured to match that of the contact at

the base of the semiconductor radiation emitter 202. In this case, at least one isolated

electrical lead 210 with electrical polarity opposite of that of the integral electrical lead 209 is

included in the package and is electrically connected to the top bond pad of the semiconductor

radiation emitter 202 via a wire bond 211. This integral electrical lead 209 may thus be a

5 cathodic or anodic lead electrically connected to the base of the semiconductor radiation

emitter 202, depending on whether the semiconductor radiation emitter has a cathode or anode

contact at its base, respectively. The isolated electrical lead 210 similarly may be an anodic or

a cathodic lead electrically connected to the top bond pad of the semiconductor radiation

emitter 202, depending on whether the semiconductor radiation emitter has an anode or

10 cathode contact at its top bond pad, respectively.

As is illustrated in Fig. 23a, the present invention is adapted to contain a plurality of

semiconductor radiation emitters 202. In a preferred embodiment, two semiconductor optical

radiation emitters are present and mounted in a cup 301 formed in heat extraction member

204. These two semiconductor optical radiation emitters both contain a cathodic contact on

15 their base that is electrically connected to the heat extraction member 204. A single integral

cathodic electrical lead 209 provides an electrical path to both semiconductor optical radiation

emitters 202. Two separate isolated anodic electrical leads 210 provide an isolated anodic

electrical path to each of semiconductor radiation emitters. As described above, wire bonds

302 provide electrical connection from the anodic electrical lead to each of the semiconductor

20 radiation emitters 202. The use of two isolated anodic electrical leads 210 facilitates the use of

two different semiconductor optical radiation emitters 202 by providing connection for an

independent current supply for each emitter. In the event that each of the semiconductor

radiation emitters 202 is of substantially the same configuration, a common anodic electrical lead may be used in addition to a common cathodic lead. Also, the invention can be modified to include more than two or three electrical leads to provide for more than two semiconductor radiation emitters of a variety of configurations.

In a preferred embodiment shown schematically in Fig. 23b, electrical leads 205 extend out of one surface of the encapsulant 203 and heat extraction member 204 extends out of the opposite surface of the encapsulant. The heat extraction member 204 may also be exposed solely or additionally through the bottom surface (surface opposite the primary direction of optical radiation emission) of the encapsulant 203.

Fig. 24a illustrates schematically an embodiment containing two semiconductor optical radiation emitters 202 which are LED chips with cathode contact on the base of the chip. The chips 202 are mounted to the heat extraction member 204 with a common cathode contact. Integral cathode electrical lead 209 forms the cathode electrical path for both chips 202. Anode connection to the each of the chips 202 is formed through wire bonds 211 to separate isolated electrical leads 210. LED chips 202 may be of the same or substantially different types. The isolation of the first and second anode electrical leads 210 allows independent control of the current flowing through each of the chips 202.

An example of LED chips connected in series is shown is Fig. 24b. In this example, a first LED chip 701 is configured with a cathode connection made through its base and an anode connection made through a bonding pad at its top surface. Second LED chip 702 is configured with an anode connection made through its base and the cathode connection made with a bonding pad on the top surface of the chip. LEDs 701 and 702 are connected to the

heat extraction member 204 with a conductive epoxy or solder. In this way, the cathode of

LED chip 701 is electrically connected to the anode of LED chip 702, both of which are

electrically connected through the heat extraction member 204 to an integral electrical lead

706. The anode bonding pad of LED chip 702 is connected to an isolated anode electrical lead

5   707 through wire bond 703. The cathode of LED chip 701 is electrically connected to isolated

cathode electrical lead 705 through wire bond 704. Optional shunt resistor 708 may be

provided by external circuitry to reduce the current through LED chip 701 relative to LED

chip 702. Further external circuitry to control the current being supplied to two or more

LEDs is outlined in co-filed U.S. Patent Application Serial No. 09/425,792, entitled

10   "INDICATORS AND ILLUMINATORS USING A SEMICONDUCTOR RADIATION

EMITTER PACKAGE," filed on October 22, 1999, by J. Roberts et al., which is hereby

incorporated herein in its entirety by reference.

An encapsulant is a material or combination of materials that serves primarily to cover

and protect the semiconductor optical radiation emitter 202 and wire bonds 211. To be useful,

15   at least a portion of encapsulant 203 must be transparent or translucent to the wavelengths of

optical radiation emitted by the semiconductor optical radiation emitter 202. For purposes of

the present invention, a substantially transparent encapsulant refers to a material that, in a flat

thickness of 0.5 mm, exhibits greater than 10 percent total transmittance at any wavelength of

energy between 100 nm and 2000 nm emitted by the one or more semiconductor optical

20   radiation emitters it covers. The encapsulant material typically includes a clear epoxy or

another thermoset material, silicone or acrylate. Alternatively, the encapsulant may

conceivably include glass or a thermoplastic such as acrylic, polycarbonate, COC or the like.

The encapsulant may include materials that are solid, liquid or gel at room temperature. The encapsulant may include transfer molding compounds such as NT 300H, available from Nitto Denko, or potting, encapsulation or other materials which start as a single part or multiple parts and are processed with a high temperature cure, two part cure, ultra-violet cure,

5   microwave cure or the like. Suitable clear encapsulants may be obtained from Epoxy Technology of Billerica, Massachusetts, from Nitto Denko America, Inc., of Fremont, California, or from Dexter Electronic Materials of Industry, California.

Encapsulant 203 provides structural integration for package 200, including retention of electrical leads 205, heat extraction member 204, emitters 202, and any conductive electrode

10   wires 211. Encapsulant 203 covers emitters 202 and partially covers heat extraction member 204 and leads 205, permitting portions of heat extraction member 204 and leads 205 to extend through the sides or back of the encapsulant.

Encapsulant 203 may provide partial optical collimation or other beam formation of electromagnetic energy emitted by emitter 202 and or reflected by the surface of heat

15   extraction member 204. For example, this beam formation may include collimating diffusing, deviating, filtering, or other optical functions. If package 200 includes a plurality of emitters 202, encapsulant 203 may provide partial mixing of energy. Encapsulant 203 also serves as a chemical barrier, sealant and physical shroud providing protection of emitters, internal adhesives such as bonds 505, bond pads 502, conductor wires, wire bonds 211 and internal

20   surfaces of heat extraction member 204 and electrical leads 205 from environmental damage due to oxygen exposure, exposure to humidity or other corrosive vapors, solvent exposure, mechanical abrasion or trauma, and the like. Encapsulant 203 provides electrical insulation.

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Encapsulant 203 may also provide a location permitting mechanical gripping or placing of package 200. Further, encapsulant 203 may provide for attaching or registering to adjacent components such as secondary optics, support members, secondary heat extractors, and the like.

In order to reduce the thermal coefficient of expansion of the encapsulant, increase the glass transition temperature of the encapsulant, or increase the thermal conductivity of the encapsulant, the encapsulant 203 may include a filler component. The filler type used depends somewhat on the optical effect that is desired, along with the physical properties desired.

In another embodiment, a portion of the overall encapsulant 203 may be composed of a substantially opaque material. As shown in Fig. 25 a first portion 801 of the encapsulant consists of a material that serves to cover a portion of each electrical lead 205 and retain the electrical leads 205 in position relative to the heat extraction member 204. This first portion does not cover the LED chip (hidden), the wire bonds (hidden) connected to the chip and any critical optical enhancement surface of the heat extraction member 204 in the immediate vicinity of the chip. Therefore, this material need not be transparent or translucent to optical radiation emitted from the chip. A second portion 804 of encapsulant 203 is transparent or translucent and covers the LED chip and wire bonds. In this embodiment, an opaque encapsulant material may form the majority of encapsulant 203. As discussed above, some opaque encapsulants may possess superior mechanical, chemical and thermal properties than clear encapsulants and may be useful for providing improved durability electrical lead retention in the harshest of applications. In this embodiment, many of the superior

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characteristics of some opaque encapsulants can be realized while still providing a mechanism

for light emitted from the LED chip to exit the device.

Dyes or pigments may be blended or dispersed within clear portions of the encapsulant

to alter the exterior appearance of the device or to tailor or augment the spectrum of radiation

5   emitted by the radiation emitter and emanating from the device. Suitable dyes for these

functions may include spectrally selective light absorbing dyes or tints well known to those

skilled in the art. Fluorescent dyes, pigments, crystals or phosphors may also be used within

the encapsulant or more particularly in a stress relieving gel to absorb energy emitted by the

optical radiation emitter and re-emit it at lower wavelengths as may be desirable in some

10   embodiments of the invention.

Upon consideration of the present invention, one skilled in the art will realize that

many various configurations and embodiments of the present invention are possible in addition

to the example just presented. By varying the number of electrical leads 205, the orientation

of the electrical leads, employing different lead bend configurations, varying the size, shape,

15   and orientation of the heat extraction member 204, using multiple emitters 202 of various

types, and varying the encapsulant configuration 203, it is possible to configure the present

invention for use in a side-looker configuration, end-looker configuration and as a through-

hole device or surface-mount device. Alternative embodiments are presented below to

illustrate the flexibility of the present invention to adapt to various system and assembly

20   configurations. These embodiments represent only a subset of the possible alternative

configurations and should not be construed as limiting the scope of the invention to those

configurations explicitly described. Fig. 26a illustrates an embodiment in which two electrical

leads extend from opposite sides of the heat extraction member 204. One electrical lead 209 is an integral electrical lead mechanically and electrically attached to the head extraction member 204 while the opposite electrical lead 210 is an isolated electrical lead. Two LED chips 202 are mounted within a cup 301 stamped into the heat extraction member 204 forming an

5 electrical contact between the cathode of each die 202, located at the base of the die, and the integral electrical lead 209. Both dies 202 are assumed to be of the same configuration and thus the anode of each die can be electrically connected to the same isolated electrical lead 210 via wire bonds 211. Fig. 26b illustrates an encapsulant 203 formed over the leadframe shown in Fig. 26a. As illustrated, the leads 209 and 210 extend from opposite sides of the

10 encapsulant 203 and the heat extraction member extends 204 from the two opposite sides orthogonal to the sides through which the leads 209 and 210 extend. Cylindrical cutouts 1601 are present in the heat extraction member 204 and encapsulant to facilitate gripping by automatic insertion equipment. A lens 401 is present in the encapsulant 203 centered over the cup 301 in the heat extraction member 204 to provide partial collimation of light emitting from

15 the LED chips 202.

An embodiment suitable for surface-mount assembly is shown is Figs. 27a and 27b. The heat extraction member 204 is configured similarly to the embodiment shown in Fig. 26, however the cup 301 is enlarged to contain three emitters. All electrical leads are isolated electrical leads 210 to maximize the thermal resistance from the circuit board, through the

20 leads, and to the emitter. Electrical contact to the cathode of each die is made through the base of the die, each of which is electrically and mechanically bonded to the heat extraction member through a wire bond 1905 and through electrical lead 1901. The anode contact of

each die 1909, 1910 and 1911 is made through wire bonds 1906, 1907, and 1908, and through electrical leads 1902, 1903, and 1904, respectively. The electrical leads are bent as shown to allow surface mount attachment to a circuit board. An encapsulant 203 covers the leadframe 201 with a lens 401 formed directly above the cup 301. The heat extraction member 204

5 extends out two sides of the encapsulant and is exposed from the back. This configuration is of particular interest when the three dies 1909, 1910, and 1911 emit at wavelengths including binary complementary wavelengths and at an enhancement wavelength or when one of the binary complement end points is synthesized by mixing light of two different colors, as described further below. The current to each die can be independently controlled through

10 isolated electrical leads 1902, 1903, and 1904 allowing the emission of light formed by a combination of a ratio of the different colors of dies 1909, 1910, and 1911.

Fig. 28 shows a cross-sectional view of the assembly shown in Fig. 27b. The cross-sectional view shown in Fig. 28 further illustrates an optional outer layer 1950 of a photoluminescent material, which serves as one or more light source. Layer 1950 may be

15 formed directly on the outer surface of encapsulant 203 or may be separately formed as a rigid or elastic film and secured to the outer surface of the device. As yet another alternative, the photoluminescent material could be incorporated into the encapsulant or it may be applied in a glob over the LED chips prior to encapsulation or dispersed within encapsulant 203.

Suitable fluorescent dyes include 8-acetoxymetyl-2,6-diethyl-1,3,5,7-tetramethyl

20 pyrromethene fluoroborate and 1,3,5,7,8-pentamethylpyrromethene-difluoroborate complex, which are commercially available from Exciton of Dayton, Ohio under the product names Exciton Pyrromethene 505 and Exciton Pyrromethene 546, respectively. A preferred

phosphor for use with the present invention includes yttrium aluminum garnet (YAG) and/or any other well-known fluorescent material. YAG is a preferred phosphor material because it may be formulated to emit light at relatively long wavelengths greater than about 505 nm and roughly corresponding to hues such as green, yellow, amber, orange or red in response to

5   absorption of light with relatively short wavelengths less than about 505 nm and roughly corresponding to hues such as blue-green, blue, and violet as well as ultraviolet wavelengths. Thus, in one embodiment utilizing LED chips that emit blue light and a YAG phosphor within or on the device, the phosphor will absorb some of the blue light and re-emit it at longer complementary wavelengths while allowing a significant portion of the blue light to emerge

10   through the device and thereby overlap and mix with the light emitted by the phosphor to create white light. Similarly, the fluorescent dyes disclosed above may be formulated to emit light having a hue that is a complement to the blue light from the LED. The specific manner of selecting binary complementary hues is explained further below. While all of the LED chips in the device could emit blue light of the same wavelength, it will be appreciated by

15   those skilled in the art that some of the LED chips could emit light of different wavelengths so as to ensure optimal excitation of the photoluminescent material that the light emitted from the device is as white as possible. Further, one of the LED chips could emit ultraviolet light as may be required by the fluorescent dye or phosphor to most efficiently emit light. Examples of other LED devices incorporating phosphors to emit white light are disclosed in U.S. Patent

20   No. 5,998,925, filed on July 29, 1997, and issued to Shimizu et al. An example of a photoluminescent source separately formed as a rigid or elastic film or cover and secured to the outer surface of an LED device is available from Asahi Rubber of Kawaguchi City,

Saitama, Japan. The photoluminescent source may also be provided in the form of a

fluorescent crystal that may be disposed on an LED chip that is used to excite the fluorescent

crystal. An example of such a structure is disclosed in "Photon Recycling Semiconductor

Light Emitting Diode (PRS-LED)" by E.F. Schubert, X. Guo, and J. Graff of Boston

5   University.

According to another embodiment of the invention, layer 1950 may include a mixture

of two or more photoluminescent sources whose emitted light has different hues and overlaps

and forms effective white light. As described further below, light of more than two different

hues may be combined to form white light. In this case, the LED chip(s) may emit UV

10 radiation without contributing to the hue of the overlapping and mixed light emitted from the

device. As yet another alternative, the LED chip(s) may emit visible light having a hue that

complements the combined hues of the plurality of photoluminescent sources.

Fig. 29 shows a light emitting assembly constructed in accordance with another

embodiment of the present invention. This assembly preferably includes an LED device 200

15 similar to those depicted in Figs. 23, 25, 26, and 27. This assembly differs in that it includes

an optical element 2000 spaced apart from LED device 200. Optical element 2000 may be a

lens and/or diffuser, or any other optical device or window. Optical element 2000 may

include a fluorescent dye or phosphor layer 2002 formed on one of its surfaces. The

fluorescent dye or phosphor layer 202 may be formed directly on the surface of optical

20 element 2000 or may be separately formed and then secured to optical element 2000.

Alternatively, a fluorescent dye or phosphor may be incorporated within optical element 2000.

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In the arrangement shown in Fig. 29, LED device 2000 serves as a solid state first light source, while the fluorescent dye or phosphor serves as a second light source. Light emitted from LED device 200 is projected onto and through optical element 2000. Some of the light incident on element 2000 is absorbed by the fluorescent dye or phosphor, which generates and

5   emits light having a wavelength of a different color. As discussed above with respect to Fig. 28, the photoluminescent material preferably emits yellow or amber light, and the LED device 200 preferably emits blue or blue-green light such that effective white light is emitted from optical element 2000. It will be appreciated by those skilled in the art, however, that many other fluorescent dyes or phosphors may be utilized and other colors of light may be

10   projected from LED device 200 with it being preferred that color selected and the fluorescent dye or phosphor that is selected together emit effective white light from optical element 2000.

In general, it is preferred that the fluorescent dye or phosphor is either formed as a separate layer on the outside of the device as shown in Fig. 28, or otherwise provided as a layer on a separate optical element or incorporated within a separate optical element, rather

15   than being incorporated within the encapsulant for the LED device. By removing the need to incorporate the fluorescent dye or phosphor within the encapsulant, a wider range of encapsulant materials may be utilized. By enabling a wider selection of encapsulant materials, an encapsulant material may be selected having thermal and optical properties that are best suited for the particular LED device. The fluorescent dye or phosphor typically tends to act as

20   a diffuser. By providing the fluorescent dye or phosphor in a separate optical element, the diffusing qualities of the fluorescent dye or phosphor may be more efficiently utilized when such diffusion is desired.

In accordance with the present invention, the plurality of conventional discrete LEDs 14 and individual LED chips 16, 202, 1909, 1910, and 1911 consists of two types whose emissions exhibit perceived hues or dominant wavelengths which are color-complementary and distinct from one another and which combine to form a metameric white light. To discuss

5   what "metameric" and "complementary" mean in the present invention, one must understand several aspects of the art of producing and mixing light and the manner in which light made from that mixing will be perceived. In general, however, it is known that the apparent "color" of light reaching an observer depends primarily upon its spectral power distribution and upon the visual response of the observer. Both of these must therefore be examined.

10   Fig. 3 is a graph plotting the relative spectral power versus wavelength for Standard "white" Illuminants A, B, and C. The Standard Illuminants have been developed by the Commission Internationale de I'Eclairage (CIE) as a reference to reduce the complexity that results from colored objects undergoing appreciable changes in color appearance as the light source which illuminates them is changed. Standard Illuminant A is a source having the same

15   relative spectral power distribution as a Planckian radiator at a temperature of about 2856K. A Planckian or blackbody radiator is a body that emits radiation, because of its temperature, according to Planck's law. True Planckian radiators are ideal abstractions, not practical sources, but many incandescent sources emit light whose spectral composition and color bears a close approximation thereto. For instance, CIE Standard Illuminant A closely approximates

20   the light emitted by many incandescent lamps such as a tungsten halogen lamp. It is convenient, therefore, to characterize the spectral power distribution of the radiation by quoting the temperature of the Planckian radiator having approximately the same relative

spectral power distribution. Standard Illuminants B and C represent "true" daylight and sunlight, respectively; however, they have too little power in the ultraviolet region compared with that of daylight and sunlight.

All of these Illuminants are variations of white light and, as can be seen from Fig. 3, have broadband spectral power distributions. Incandescent light sources are typically solids that emit light when their temperatures are above about 1000 K and the amount of power radiated and the apparent color of this emission is directly related to the source temperature. The most familiar incandescent light sources are the sun, flames from a candle or gas lamp, and tungsten filament lamps. Such sources, similar to CIE Standard Illuminants A, B and C in Fig. 3, have spectral power distributions which are relatively constant over a broad band of wavelengths, are often referred to as broadband sources, and have colors which are perceived as nearly achromatic or white. Given the diversity of white-light sources and the associated range of near-white colors which are de facto accepted as white in various areas of practice, a color shall be deemed as white within the scope of the present invention if it is substantially indistinguishable from or has color coordinates or tristimulus values approximately equal to colors within the white color boundary translated from the revised Kelly chart, within the SAE J578 achromatic boundaries, along the blackbody curve including Planckian radiators at color temperatures between 2000 K and 10,000 K, sources close to Standard Illuminants A, B, C, D_{65}, and such common illuminants as fluorescent F1, F2, F7, high pressure sodium lamps, xenon lamps, metal halide lamps, kerosene lamps or candles. These are all well known in the art and will be referenced and discussed hereinafter.

Unlike the other sources discussed, LEDs are narrow bandwidth sources. In addition

to Standard Illuminants A, B, and C, Fig. 3 shows the spectral power distribution of two

LEDs, one emitting a narrow-bandwidth radiation with a peak spectral power emission at 592

nanometers (nm) and the other at 488 nm. As can be seen by examination of this figure, the

5   characteristic spectra of LEDs is radically different from the more familiar broadband sources.

Since LEDs generate light by means of electroluminescence (instead of incandescence,

pyroluminescence or cathodoluminescence), the emission spectra for LEDs are determined by

the band gap of the semiconductor materials they are constructed of, and as such are very

narrow-band. This narrow-band visible light emission characteristic is manifested in a highly

10   saturated appearance, which in the present invention means they have a distinctive hue, high

color purity, i.e., greater than about 0.8, and are therefore highly chromatic and distinctly

non-white. Despite the narrow-band attributes of LED light, a combination of the emissions

of two carefully selected LEDs, or of one LED and a fluorescent dye or phosphor, can

surprisingly form illumination which appears white in color, with color coordinates

15   substantially identical to Standard Illuminants A, B or C. Fig. 30 shows the relative spectral

power of two light sources, which, as discussed above, may include various combinations of

electroluminescent sources or other solid-state sources and/or photoluminescent sources.

The reason that light from highly chromatic narrow-band light sources can be perceived

as white light when combined is that, as mentioned hereinabove, the apparent color of light

20   such as from a self-luminous source depends upon the visual response of the observer, in

addition to the characteristics of the light from the source. In addition, the apparent color of a

non-self-luminous object or surface (one which must be illuminated by a separate source in

order to be seen) is slightly more complicated and depends upon the visual response of the

observer, the spectral reflectance of the object or surface in question, and the characteristics of

the light illuminating the object or surface. As illustrated in Figs. 4a, 4b, and 4c, if a surface

or object is a "neutral gray" diffuse reflector, then it will reflect light having a composition

proportionally the same as the source which illuminates it, although invariably dimmer. Since

the relative spectral power distribution of the light reflected from the gray surface is the same

as the illuminating source, it will appear to have the same hue as the illuminating source itself.

If the illuminating source is white, then the surface will appear white, gray, or black

(depending on its reflectance). Fig. 4c shows the resultant spectral power distribution of the

light emitted from a plurality of amber and blue-green LEDs and subsequently reflected from a

50 percent neutral gray target surface.

As stated hereinabove, the visual response of an observer affects the apparent color of

emitted and reflected light. For humans, the sensors or receptors in the human eye are not

equally sensitive to all wavelengths of light, and different receptors are more sensitive than

others during periods of low light levels. Cone receptors are active during high light levels or

daylight and are responsible for color perception. Rod receptors are active during low light

levels and have little or no sensitivity to red colors, but have a significant sensitivity to blue

light. Fig. 5 is a graph plotting the relative sensitivity of a "standard observer" versus

wavelength for the spectral luminous efficiency functions. The curve represented by V

represents a standard observer's visual sensitivity to stimuli seen under photopic (or high light

level) conditions of vision, and the curve V' represents a standard observer's visual sensitivity

to stimuli seen under scotopic (or low light level) conditions of vision. As can be seen, the

photopic response (V) has a nearly Gaussian shape with a peak at about 555 nm and the

scotopic response (V') has a peak at about 508 nm. This difference between relative spectral

sensitivity during photopic and scotopic conditions amounts to an enhanced blue response and

diminished red response during darkness and is known as the Purkinje phenomenon. Scotopic

5   conditions exist when observed surfaces have surface luminances of less than a few hundredths

of a candela per square meter. Photopic conditions exist when observed surfaces have surface

luminances of more than about 5 candelas per square meter. A transition range exists between

photopic and scotopic vision and is known as mesopic (or middle light level) vision,

represented by the intermediate curve in Fig. 5, which is an estimated typical mesopic

10   response. Another primary difference between photopic, scotopic, and mesopic vision is the

absence of color discrimination ability in scotopic conditions (very low light levels) and

reduced color discrimination abilities in mesopic conditions. This will be discussed further

hereinbelow.

The differences between photopic, mesopic, and scotopic viewing conditions are

15   relevant to the present invention because an illuminator is used to illuminate areas during low

light level conditions. Thus, before any illumination, the environment represents scotopic

conditions of vision and during full illumination (after the eye has had time to adapt to the

increased illumination), the environment is in the photopic conditions of vision. However,

during the time the eye is adapting, and on the "outer fringes" of the illuminated region even

20   after adaptation, the environment is in the mesopic conditions of vision. The eye's varying

sensitivities to these different levels of illumination are very important in designing a proper

illuminator.

The colors perceived during photopic response are basically a function of three

variables, corresponding to the three different types of cone receptors in the human eye.

There are also rod receptors, however, these only become important in vision at low light

levels and are typically ignored in color evaluations at high light levels. Hence, it is to be

5   expected that the evaluation of color from spectral power data should require the use of three

different spectral weighting functions. Fig. 6 plots the relative response versus wavelength of

the CIE color-matching functions for the 1931 standard 2 degree observer. The color-

matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ relate to the sensitivity of the three types of cone

receptors in the human eye to various wavelengths (λ) of light through a series of transforms.

10   As can be seen by the curves in Fig. 6, the color-matching function $\bar{x}(\lambda)$ has a moderate

sensitivity at about 450 nm, almost no sensitivity around 505, and a large sensitivity around

600 nm. Another color-matching function $\bar{y}(\lambda)$ has a Gaussian shape centered around 555

nm, and the third color-matching function $\bar{z}(\lambda)$ has a significant sensitivity centered around

445 nm.

15   As stated earlier, it is known that by combining a red color (such as a monochromatic

source located at 700 nm and hereinafter designated as R), a green color (such as a

monochromatic source located at 546 nm and hereinafter designated as G), and a blue color

(such as a monochromatic source located at 435 nm and hereinafter designated as B) in proper

ratios, virtually any color can be exactly matched. The necessary proportions of R, G, and B

20   needed to match a given color can be determined by the above-described color matching

functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ as in the following example.

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First, the amount of power per small, constant-width wavelength interval is measured with a spectraradiometer throughout the visible spectrum for the color to be matched. Then, the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are used as weighting functions to compute the tristimulus values X, Y and Z by further using the following equations:

$$X = k[P_1 x(\lambda)_1 + P_2 x(\lambda)_2 + P_3 x(\lambda)_3 + ... P_n x(\lambda)_n \qquad [1]$$

$$Y = k[P_1 y(\lambda)_1 + P_2 y(\lambda)_2 + P_3 y(\lambda)_3 + ... P_n y(\lambda)_n \qquad [2]$$

$$Z = k[P_1 z(\lambda)_1 + P_2 z(\lambda)_2 + P_3 z(\lambda)_3 + ... P_n z(\lambda)_n \qquad [3]$$

where k is a constant; $P_{1,2,3,n}$ are the amounts of power per small constant width wavelength interval throughout the visible spectrum for the color to be matched, and $\bar{x}(\lambda)_{1,2,3,n}$, $\bar{y}(\lambda)_{1,2,3,n}$ and $\bar{z}(\lambda)_{1,2,3,n}$ are the magnitudes of the color-matching functions (taken from the curves of Fig. 6) at the central wavelength of each interval. Finally, the approximate desired proportions of the above-described monochromatic sources R, G, and B are calculated from the above computed X, Y, and Z tristimulus values using the following equations:

$$R = 2.365X - 0.897Y - 0.468Z \qquad [4]$$

$$G = -0.515X + 1.426Y + 0.0888Z \qquad [5]$$

$$B = 0.005203X - 0.0144Y + 1.009Z \qquad [6]$$

Therefore, the color-matching functions of Fig. 6 can be used as weighting functions to determine the amounts of R (red), G (green), and B (blue) needed to match any color if the amount of power per small constant-width interval is known for that color throughout the spectrum. Practically speaking, R, G, and B give the radiant intensities of 3 monochromatic

light sources (such as lasers) with emissions at 700 nm, 546 nm and 435 nm, respectively, needed to match the chosen color.

Referring again to Fig. 3, the reason that the combined emissions from the two depicted LEDs will look like a broadband white-light source, even though they possess radically different spectral compositions, is because their combined emissions possess the same tristimulus values (as computed by Equations 1-3) as those of the broadband source Standard Illuminant B. Similarly, referring to Fig. 30, the depicted spectra from the two light sources produces white light. This phenomenon is known as metamerism and is an essential aspect of the present invention.

Metamerism refers to a facet of color vision whereby two light sources or illuminated objects may have entirely different emitted or reflected spectral power distributions and yet possess identical tristimulus values and color coordinates. A result of metamerism is that additive mixtures of light from two completely different pairs of luminous sources (with their associated distinct spectra) can produce illumination having exactly the same perceived color. The principles and application of additive color mixing and metamerism to the present invention are discussed in greater detail later in this disclosure.

Fig. 7 is a CIE 1976 uniform chromaticity scale (UCS) diagram, commonly referred to as the u', v' diagram. The u', v' diagram is used to conveniently provide numerical coordinates that correlate approximately with the perceptible color attributes, hue, and saturation. A UCS diagram is also used to portray the results of color matching computations, color mixing, and metamerism in a form that is well recognized in the art and is relatively easy to understand and use. Of course, exact color perceptions will depend on the viewing

conditions and upon adaptation and other characteristics of the observer. In addition, other color coordinate systems are available, such as the CIE 1931 2 degree Chromaticity Diagram (commonly referred to as the x, y chart), CIELAB, CIELUV, Hunter and Munsell systems, to name a few. For the sake of simplicity, the present invention is further described hereinbelow using the CIE 1976 UCS system. However, it should be understood that teachings of the present invention apply regardless of the color system used to describe the invention and therefore are not limited by this exclusive use of the CIE 1976 UCS system.

Referring again to Fig. 7, the location of a color on the u', v' diagram is obtained by plotting v' and u', where:

$$u' = 4X/(X + 15Y + 3Z) = 4x/(-2x + 12y + 3) \qquad [7]$$

$$v' = 9Y/(X + 15Y + 3Z) = 9y/(-2x + 12y + 3) \qquad [8]$$

and where X, Y, and Z are the tristimulus values described hereinabove (x and y correspond to the CIE 1931 Chromaticity x, y coordinates and are provided for convenient conversion). Thus, any color can be described in terms of its u' and v' values. Fig. 7 shows the respective positions on the u', v' diagram for the Planckian Locus, the SAE J578 boundaries for achromatic white light, Standard Illuminants A, B, and C, as well as the locus of binary additive mixtures from blue and red LEDs are shown. As can be seen, Standard Illuminants A, B, and C, closely corresponding to blackbody radiators, lie along the Planckian Locus.

The Planckian Locus is a curve on the u', v' diagram connecting the colors of the Planckian radiators at various temperatures, a large portion of which traverses the white, or achromatic region of the diagram. The SAE J578 achromatic white boundaries shown were translated from CIE 1931 Chromaticity x, y coordinates using Equations 6 and 7 hereinabove

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and are generally used to define what is an acceptable white light for automotive purposes (although many automotive white lights in use fall outside these boundaries).

Also shown in Fig. 7 is the range of colors producible by a hypothetical additive color combination of red (660 nm) and blue (460 nm) LEDs. Fig. 7 clearly shows how far off the Planckian Locus and the SAE J578 achromatic boundaries that the colors produced by this combination fall. In fact, the locus of binary additive mixtures from these blue and red LEDs has perceived hues of red, pink, purple, violet, and blue. This system would therefore not be suitable as the improved white-light emitting assembly of the present invention.

A white-light emitting assembly might in fact be constructed, however, from a three-color system. As stated hereinabove, an R-G-B combination can produce almost every conceivable color on the 1976 UCS diagram. Such a system would be complex and expensive, however, and/or would suffer from unacceptable manufacturing variations inherent to R-G-B systems.

This is illustrated best by reference to Fig. 8, which again shows the CIE 1976 UCS diagram, the Planckian Locus, and the translated SAE J578 boundaries. In addition, the locus of ternary additive mixtures producible from hypothetical R-G-B LED configuration combinations and estimated manufacturing variations associated therewith are shown. Due to various uncontrolled processes in their manufacture, LEDs of any given type or color (including red, green, and blue) exhibit large variations from device to device in terms of their radiant and luminous intensities, and smaller variations in hue. As can be confirmed by reference to typical LED product literature, this variation can represent a 200 percent change in intensity from one LED to another or from one batch to another, even if the compared

LEDs are of the same type and hue. Equations 7 and 8 clearly show the dependency of a color's u', v' coordinates upon its tristimulus values X, Y and Z, and Equations 4-6 show a linking dependency to source power (or intensity). Thus, variations in R-G-B LED intensity and hue will cause variations in the u', v' color coordinates of their mixed light. Therefore, it would be very difficult to construct a large number of R-G-B LED illuminators with any assurance that their light would reproducibly match a desired color such as white. This is illustrated by the shaded area in Fig. 8 and is referred to as the Locus of R-G-B LED Manufacturing Variation.

Thus, with a red, green, and blue combination, white light can be reproducibly created only if extraordinary measures were invented to ensure that the additive color mix proportions are maintained during LED and light emitting assembly production. This would involve extensive measurement and for every LED to be used or perhaps incorporation of active electronic control circuits to balance the LED output in response to some process sensor. The extra costs and complexity associated with such an approach, combined with the obvious complexity of supplying three different types of LEDs through inventory and handling systems are daunting and render such a configuration unsuitable for the various applications of the present invention.

In the broadest sense, therefore, the present invention relates to producing nearly achromatic light by additively combining complementary colors from two types of colors of saturated LED sources or their equivalents. By complementary we mean two colors that, when additively combined, reproduce the tristimulus values of a specified nearly achromatic stimulus, *e.g.*, a reference white. By appropriately tailoring the proportions of light from each

of these two complementary colors, we produce a metameric white resultant color, or alternatively any other resultant color between the two complementary color stimuli (depending on the proportion of the additive mixture). Although the saturated sources of greatest interest are LEDs, whose emissions are narrow-band, the present invention clearly

5   teaches that similar results could be achieved with other appropriately chosen narrow-band light sources.

Fig. 9 is a CIE 1976 UCS diagram which broadly illustrates how the additive mixture of light from two LEDs having complementary hues can be combined to form a metameric white light. Also shown are the approximate boundaries of the "white" color region which

10   has been translated from the revised Kelly chart and the CIE 1931 x, y Chromaticity Diagram. The Kelly chart and 1931 x, y Chromaticity Diagram are not shown but are well known in the art. Fig. 9 further depicts a first embodiment of the present invention utilizing a combination of one or more LEDs whose emissions have peak wavelengths of approximately 650 nm and 500 nm and perceived hues of red and green. As the diagram shows, this produces a "white"

15   light located between Standard Illuminants A and B on the Planckian Locus.

It should be understood, however, from the above discussions that substantial variations inherent to conventional discrete and individual chip LEDs will cause changes in the coordinates of the resultant additive color mixture. The 650 nm LED depicted in Fig. 9 may fall into a range of LEDs with peak wavelengths ranging from 635 to 680 nm whose light has

20   the hue of red, and the 500 nm LED depicted in Fig. 9 may fall into a range of LEDs with peak wavelengths ranging from 492 nm and 530 nm and whose light has the hue of green. In this embodiment, this variation, and more particularly the pronounced intensity manufacturing

variations of the plurality of LEDs used, will cause the coordinates of the resultant mixture to traverse the u', v' chart in a direction generally substantially perpendicular to the Planckian Locus into either the yellowish-pink or the yellowish-green region of the u', v' diagram. Fortunately, as discussed hereinabove, there is some tolerance in the human visual system for

5   acceptance of slightly non-white colors as effectively white. It should be understood that a similar mixture of red-orange or red LED light (with a peak wavelength between 600 nm and 635 nm or between 635 and 680 nm, respectively) with a complementary green LED light (with a peak wavelength between 492 nm and 530 nm) or a mixture of yellow-green or yellow LED light (with a peak wavelength between 530 nm and 572 nm) with a purple-blue or blue

10   LED light (with a peak wavelength between 420 nm and 476 nm) can be made to function in the same manner to produce similar results and are included in the scope of this embodiment of the present invention. Thus, a system as described herein would function as an embodiment of the present invention if the other parameters were also met (such as projecting effective illuminance).

15   A more preferred embodiment is illustrated in Fig. 10 which is a CIE 1976 UCS diagram illustrating a binary complementary combination of light from a plurality of LEDs of two different types having peak wavelengths of 592 nm and 488 nm and perceived hues of amber and blue-green, respectively, such that the light from the two types of LEDs overlaps and mixes with sufficient intensity and appropriate proportion to be an effective illuminator

20   projecting white light. Although their spectra are very different from that of any Standard Illuminant, the mixed output of an amber LED and a blue-green LED appears surprisingly to be almost identical to Standard Illuminant B or C when viewed by a "standard" human

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observer. On Fig. 10, the u', v' coordinates of the nominal mixture occur at the intersection of this dashed line and the Planckian Locus, between Standard Illuminants A and B. Since the u', v' coordinates of the LED colors in this embodiment mark the endpoints of a line segment which is substantially coaxial with the Planckian Locus and the long axis of the SAE J578

5   achromatic white boundaries, any intensity variation deriving from manufacturing variations will produce colors along an axis remaining in close proximity to the Planckian Locus and within the boundaries of other widely-accepted definitions of white. This significantly simplifies the manufacturing process and control electronics associated with the light emitting assembly, which decreases the overall production cost and makes commercialization more

10   practical. In addition, we have found that of the many types and hues of LEDs presently available, the two preferred types of LEDs for the present invention have very high luminous efficacy in terms of light emitted compared to electrical power consumed. These are transparent substrate AlInGaP amber LEDs available from Hewlett Packard Inc., Optoelectronics Division located in San Jose, California, and GaN blue-green LEDs available

15   from Nichia Chemical Industries, LTD located in Anan-shi, Tokushima-ken, Japan.

Fig. 11 further amplifies this embodiment of the invention by illustrating issues of manufacturing variation within the context of other definitions of white. The hatched lines between amber (peak emission between 572nm and 600 nm) and blue-green (peak emission between 476 nm and 492 nm) show the range in LED hue variations at either endpoint for this

20   embodiment which would be generally capable of producing metameric white light. Since LEDs are solid-state devices comprising a base semiconductor material and one or more dopants which impact the spectral emission characteristics of the LED, the level of doping and

other process parameters can be adjusted to intentionally modify the peak wavelength emitted

by the LED. Furthermore, as discussed hereinabove, certain random variations also occur,

affecting the additive color mixture. In this embodiment of the present invention, however,

larger than normal variations can be tolerated. This is because a large part of the area between

5   the hatched lines and within the monochromatic locus of the chart overlaps the areas

commonly perceived as and referred to as white, such as the Planckian Locus, the marked

region corresponding to the translated Kelly boundaries for the color white, or the shaded

region corresponding to the translated SAE J578 boundaries for achromatic white. Therefore,

all of the additive colors resulting from reasonable variations in the LED intensity and hue of

10   this embodiment fall within one of the white regions. The figure thus clearly illustrates how

there can be a range of amber LEDs whose hues are complementary with a range of blue-

green LED hues which, when combined, form substantially white light.

The most preferred embodiment of the present invention uses a binary complementary

combination of light from a plurality of LEDs of two different types having peak wavelengths

15   of 584 nm and 483 nm and perceived hues of amber and blue-green, respectively, such that the

light from the two types of LEDs overlaps and mixes with sufficient intensity and appropriate

proportion to project effective white illumination. When plotted on a color chart, the u', v'

coordinates of the light emitted by the LEDs of this embodiment mark the endpoints of an

interconnecting line segment that is coaxial with the portion of the Planckian Locus which

20   traverses Standard Illuminants A, B and C, as shown in Fig. 12.

As discussed hereinabove, intensity and hue variations are a natural by-product of

random variations occurring in production of LEDs. For this embodiment of the present

invention, however, the need for intensive in-process manufacturing controls and electronic

controls integrated onto an illuminator assembly to compensate for inherent manufacturing

variations for LEDs is largely eliminated. This is illustrated by the substantially coaxial

relationship between the line connecting the u', v' coordinates of the preferred LEDs of the

5   present invention and a best-fit linear approximation to the portion of the Planckian Locus

from 2000 K to 10000 K. In addition, process controls, inventory management, materials

handling, and electronic circuit design are further simplified by only having two colors to

manipulate rather than three. This substantial simplification decreases manufacturing costs

significantly and augments the present invention's capability for creating and projecting white

10   light - the only color of light desired for the practical embodiments of the present invention.

The flexibility of the present invention is further amplified by application of additive

color techniques to synthesize the end member constituents of the binary-complementary LED

light mixture described hereinabove. This approach is best understood by reference to Fig.

13, which illustrates the use of additive sub-combinations of non-complementary LEDs to

15   form effective binary complements corresponding to the two types of LEDs discussed

hereinabove. Hues 1-7 represent the emissions from LEDs as follows: hue 1 is purple-blue or

blue for LEDs with a peak wavelength between 420 nm and 476 nm, hue 2 is blue-green for

LEDs with a peak wavelength between 476 nm and 492 nm, hue 3 is green for LEDs with a

peak wavelength between 492 nm and 530 nm, hue 4 is yellow-green or yellow for LEDs with

20   a peak wavelength between 530 nm and 572 nm, hue 5 is amber for LEDs with a peak

wavelength between 572 nm and 605 nm, hue 6 is red-orange for LEDs with a peak

wavelength between 605 nm and 635 nm, and hue 7 is red for LEDs with a peak wavelength

between 635 nm and 680 nm. An additive mixture of light from one or more LEDs with hues 6 or 7 and one or more LEDs with hue 4 can be combined to form light having the same hue and substantially the same saturation as LED light with hue 5. Thus, an equivalent or substitute for the amber LEDs of Fig. 11 is synthesized by additive combination of the emitted light from two types of LEDs whose emissions are characterized by hues 6 or 7 and 5, respectively. In a similar fashion, an additive mixture of light from one or more LEDs with hue 1 and one or more LEDs with hue 3 can be combined to form light having the same hue and substantially the same saturation as LED light with hue 2, thus synthesizing an equivalent or substitute for the blue-green LEDs of Fig. 11.

An example of this synthetic end member technique is depicted in Figs. 30 and 31. The emission spectra of a binary complementary light source that may for example be an LED device comprising amber and blue-green LED chips is illustrated at Fig. 30. The emission of a similar device further incorporating a photoluminescent light source such as a fluorescent dye is illustrated at Fig. 31. While the emissions depicted in each of these figures can be perceived as white light, it can be seen by comparison that the spectra depicted in Fig. 31b (which is the sum of the spectra shown in Fig. 31a) is broader than that shown in Fig. 30. Such a broadening of a light source spectra can be useful such as to improve rendering for a device in which two binary complementary LEDs are utilized. In this example, the phosphor or fluorescent dye improves rendering by shifting and re-emitting some of the light it absorbs, broadening the overall spectrum of the combination of light emitted by the resultant light emitting assembly.

When a non-complementary sub-combination of LED light is used to synthesize an equivalent or substitute to one of the end members of the aforementioned binary complementary mixture, or alternately when a fluorescent media us used within a binary complementary light assembly to broaden or shift the assembly spectra, then the combination

5 of light from the light assembly mixes to form metameric white illumination. This variant of binary complementary systems can be important in commercial practice, where prolonged supply disruptions are common for LEDs of one variety or another due to explosive growth in market demand or insufficient LED manufacturer capacity. As explained herein, such a disruption can be mitigated in the case of the present invention by the use of sub-combinations

10 of more readily available alternative LEDs or photoluminescent light sources to form equivalent complements. Again, comparing Figs. 30 and 31, for example, it can be seen that 605 nm "orange" LEDs might be used in conjunction with a fluorescent media having a yellow or amber peak emission instead of utilizing amber LEDs with a peak emission near 592 nm. This would be of great value if orange LED chips were more widely available in the desired

15 intensity than amber LED chips.

Figs. 14a-14c illustrate an illuminator of the present invention incorporated as a maplight within an automotive interior rearview mirror, however, it should be understood that the illuminator of the present invention may alternatively be incorporated into an automotive exterior rearview mirror as a security light or "puddle" light. The automotive rearview mirror

20 130 is provided with a housing 132 composed of a back wall 132a, a peripheral sidewall 132b having a top, bottom and endwall portion. The peripheral sidewall 132b defines a front opening adapted to receive a mirror element 134. A mounting bracket (not shown) may be

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provided for mounting the rearview mirror 130 on an automobile windshield (not shown) or headliner (not shown). The mirror element 134 may be a conventional prismatic mirror element as shown in Figs. 14a and 14b or may be an electro-optic glare reducing mirror element such as an electrochromic or liquid crystal dimming mirror element well known in the

5   art. It should be understood that, although Fig. 14 shows a conventional prismatic mirror element, the mirror element 134 is intended to represent any mirror element well known in the art including an electrochromic glare-reducing mirror element without deviating from the scope of the present invention.

If an electrochromic glare-reducing mirror element is substituted as mirror element

10   134, the following patents provide an exemplary teaching of electro-optic devices in general and, more specifically, electrochromic rearview mirrors and associated circuitry: U.S. Patent No. 4,902,108, entitled "SINGLE-COMPARTMENT, SELF-ERASING, SOLUTION-PHASE ELECTRO-OPTIC DEVICES SOLUTIONS FOR USE THEREIN, AND USES THEREOF," issued February 20, 1990, to H.J. Byker; Canadian Patent No. 1,300,945,

15   entitled "AUTOMATIC REARVIEW MIRROR SYSTEM FOR AUTOMOTIVE VEHICLES," issued May 5, 1992, to J.H. Bechtel et al.; U.S. Patent No. 5,128,799, entitled "VARIABLE REFLECTANCE MOTOR VEHICLE MIRROR," issued July 7, 1992, to H.J. Byker; U.S. Patent No. 5,202,787, entitled "ELECTRO-OPTIC DEVICE," issued April 13, 1993, to H.J. Byker et al.; U.S. Patent No. 5,204,778, entitled "CONTROL SYSTEM FOR

20   AUTOMATIC REARVIEW MIRRORS," issued April 20, 1993, to J.H. Bechtel; U.S. Patent No. 5,278,693, entitled "TINTED SOLUTION-PHASE ELECTROCHROMIC MIRRORS," issued January 11, 1994, to D.A. Theiste et al.; U.S. Patent No. 5,280,380, entitled "UV-

STABILIZED COMPOSITIONS AND METHODS," issued January 18, 1994, to H.J. Byker;

U.S. Patent No. 5,282,077, entitled "VARIABLE REFLECTANCE MIRROR," issued

January 25, 1994, to H.J. Byker; U.S. Patent No. 5,282,077, entitled "VARIABLE

REFLECTANCE MIRROR," issued January 25, 1994, to H.J. Byker; U.S. Patent

5   No. 5,294,376, entitled "BIPYRIDINIUM SALT SOLUTIONS," issued March 15, 1994, to

H.J. Byker; U.S. Patent No. 5,336,448, ENTITLED "ELECTROCHROMIC DEVICES

WITH BIPYRIDINIUM SALT SOLUTIONS," issued August 9, 1994, to H.J. Byker; U.S.

Patent No. 5,434,407, entitled "AUTOMATIC REARVIEW MIRROR INCORPORATING

LIGHT PIPE," issued January 18, 1995, to F.T. Bauer et al.; U.S. Patent No. 5,448,397,

10   entitled "OUTSIDE AUTOMATIC REARVIEW MIRROR FOR AUTOMOTIVE

VEHICLES," issued September 5, 1995, to W.L. Tonar; and U.S. Patent No. 5,451,822,

entitled "ELECTRONIC CONTROL SYSTEM," issued September 19, 1995, to J.H. Bechtel

et al. Each of these patents is commonly assigned with the present invention and the

disclosures of each, including the references contained therein, are hereby incorporated herein

15   in their entirety by reference.

In accordance with one embodiment of the present invention, the bottom portion of the

housing peripheral sidewall 132b of mirror 130 has two openings 140a and 140b disposed

therein such that a portion of the vehicle is illuminated therethrough. Two sets of a plurality

of LEDs 114 are disposed within the housing 130 such that when energized by a power supply

20   (not shown) and/or electronic control 122, a portion of the vehicle interior is illuminated

through openings 140a and 140b. As is shown in Fig. 14a, openings 140a and 140b are

disposed toward opposite ends of the bottom portion of peripheral sidewall 132b such that

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opening 140a illuminates the driver portion of the vehicle interior and opening 140b

illuminates the passenger portion of the vehicle. For mirrors designed for certain foreign

vehicles having a right-hand drive configuration, of course, opening 140a would correspond to

the passenger portion of the vehicle and opening 140b would correspond to the driver portion.

5   Incorporating LEDs 114 into housing 132 to illuminate the vehicle interior through

openings 140a and 140b has a number of advantages over prior art incandescent maplights as

follows.

Incandescent illuminators operate by heating a metal filament, and a significant portion

of this heat radiates, conducts, and convects away from the bulb. This heat must be dissipated

10   to reduce the chance of damage to the mirror assembly or other components within the mirror

housing, e.g., electrochromic glare-reducing element, compass, etc. Mechanisms for

dissipating this heat are features such as heat sinks which assist with conductive and convective

heat transfer, air vents or blowers which improve convection, or certain optical components or

coatings which can help with radiative heat transfer. All of these typically add a

15   disadvantageous combination of weight, volume, cost or complexity to the mirror assembly.

In addition, incandescent lights radiate light equally in all directions. This causes

several problems such as having to incorporate large reflectors to direct the light toward the

vehicle occupants. These reflectors in turn occupy critical space and add weight to the mirror

assembly. Furthermore, light from the incandescent source that is not reflected by the

20   reflector toward the occupants can cause glare to the driver and can also inhibit the proper

operation of any electrochromic glare-reducing layer by causing a false input to the glare

and/or ambient light sensors incorporated therein. LEDs, whether the conventional discrete

type with integral optics or individual semiconductor die with separate optics, are very small and therefore the reflector assemblies or other optics used with them do not add significantly to the weight or volume of the mirror assembly. In addition, several LED chips may be incorporated into one package for even further reduction in size.

5   As weight is added to the mirror assembly, greater stress is placed upon its mounting structures and its resonant vibration characteristics change. Greater stress on the mounting mechanism due to any increase in weight can lead to premature failure of the mounting mechanism, particularly if the mount is of the type which attaches by means of adhesive to the interior surface of the windshield. The added weight can also cause a decrease in resonant

10   frequency and increase in vibrational amplitude, degrading the clarity of images reflected in the mirror during vehicle operation. In addition to being a safety concern, premature mount failure or increased vibration signature clearly would be displeasing to the vehicle owner.

As automobiles become more complex, more and more option components are being incorporated in the mirror housing. For example, remote keyless entry systems, compasses,

15   indicia for direction, tire pressure, temperature, etc. are being incorporated into mirror housings. Since there is limited space in a mirror housing, decreasing the volume of every component within the housing is necessary. The additional space required to cool an incandescent lamp and collimate its light severely complicates the inclusion of these other desirable features.

20   Conversely, LEDs do not operate at high temperatures and thus create fewer heat dissipation problems and the space problems associated with heat dissipation measures.

Because individual LED chips are extremely small, typically measuring 0.008 inches x 0.008 inches x 0.008 inches, they approximate a point source better than most incandescent filaments and the collimating optics (such as lenses and reflectors) used with either the conventional discrete LEDs or chip-on-board LEDs can perform their intended function with

5   much greater effectiveness. The resultant LED illuminator projects a more uniform and precisely tailored and directed intensity distribution.

LEDs have an extraordinarily long life compared with the typical 1,000 to 2,000 hour life for incandescent lights. A typical LED will last anywhere from 200,000 to 2,000,000 hours, depending on its design, manufacturing process, and operating regime.

10   LEDs are also much more rugged than incandescent bulbs, and they are more resistant to mechanical shock and vibration, thermal shock, and impact from flying debris. They further are virtually impervious to the on-off switching transients which cause substantial reliability problems for incandescent systems. The lifetime and reliability advantage is significant, and when coupled with their inherent ruggedness, the advantage of using LEDs becomes striking.

15   Comparing an amber LED (Part No. HLMT-DL00, from Hewlett Packard) with a 0.72W power dissipation from the circuit in Fig. 21, with a Philips type 192 lamp run at 13.0 Volt, using the method set forth in Military Specification HDBK-217F-1, illustrates the significant disparity in calculated failure rate. The results show that the amber LED would have a 0.17 percent failure rate whereas the incandescent lamp would have a failure rate of

20   99.83 percent over the same time period.

In exterior rearview mirrors, these issues are further amplified, due to the more severe shock and vibration conditions, as well as environmental exposures such as rain, snow,

temperature fluctuations, UV radiation exposure, and humidity which prevail in the outdoor environment. This makes incorporating an incandescent lamp into an outside rearview mirror even more difficult in that it must be protected from these factors. Regardless of the measures undertaken to prevent failure of incandescent lamps incorporated into an automotive interior

5   mirror map light assembly or into an automotive exterior mirror security light assembly, these lamps have such a short life that means must be provided for replacing the light bulbs without having to replace the entire mirror assembly. Unfortunately, a design which allows for easy replacement typically is not as effective at protection, further increasing the probability of early failure. This makes the task of protecting the bulb from environmental factors difficult

10   and costly to design and manufacture. LEDs, on the other hand, have an extremely long life and are generally very highly resistant to damage from vibration, shock, and other environmental influences. Therefore, LEDs last much longer than the life of the mirror assembly and the vehicle itself, and the design of the mirror assembly need not include means for replacing the LEDs.

15   White-light LED illuminators of the present invention can be very compact and thus can be incorporated into automotive rearview mirrors in a manner with much greater aesthetic appeal than with prior art incandescent systems.

          Finally, incandescent lamps possess very low electrical resistance when first energized until they heat up to incandescence and therefore draw an inrush current which can be 12 to 20

20   times their normal operating current. This inrush places tremendous thermo-mechanical stresses on the filament of the lamp, and commonly contributes to premature failure at a fraction of rated service life (much shorter than the service life of a vehicle). Inrush current

also stresses other electronic components in or attached to the illuminator system such as the power supplies, connectors, wire harnesses, fuses and relays such that all of these components must be designed to withstand repeated exposure to this large transient. LEDs have no inrush current and therefore avoid all of these issues.

The "bloom time" for an incandescent lamp or time it takes for the lamp to become fully bright after its supply voltage is initially applied is very long—in excess of .2 seconds for many lamps. Although extremely fast response times are not mandatory in a vehicle maplight, a fast response characteristic is advantageous for electronic control of intensity and color mix proportions as discussed below. Further, certain binary complementary metameric white LED illuminator applications such as lamps aiding surveillance may benefit from a strobe-like ability to become bright quickly upon electronic activation.

In accordance with one embodiment of the present invention, the plurality of LEDs 114 behind each opening 140a and 140b may be any combination of two types of LEDs whose emissions have hues which are complements to one another (or a combination of equivalent binary complements formed from non-complementary sub-combinations of LED light) such that the light from the two groups combines to project effective white illumination; however, as stated above, the preferred LEDs 114 disposed in each of the openings 140a and 140b are a combination of amber LEDs and blue-green LEDs. When energized, these two types of LEDs produce light having hues which are color complements, and, when combined in the proper proportions, their resultant beams overlap and mix with sufficient intensity to be an effective illuminator projecting substantially white light. More specifically, at least two amber LEDs such as a transparent substrate AlInGaP type from Hewlett Packard Corporation,

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Optoelectronics Division should be combined with at least one blue-green LED such as a GaN type LED from Nichia Chemical Industries, Ltd. in each of openings 140a and 140b; the most preferred combination is 3 or 4 amber LEDs to 2 or 3 blue-green in each of openings 140a and 140b. This combination produces white light with an effective illumination to illuminate a

5   portion of a vehicle's interior to assist the occupants in reading maps, books, and the like.

As stated above, an area of effective illumination occurs at some distance away from the illuminator. Effective illumination is an important aspect of the present invention and, in the art of automotive maplights, is partly determined by auto manufacturer specifications. For example, Fig. 15 indicates what one auto manufacturer requires as an acceptable illuminance

10   for a rearview mirror having an integral map lamp. The illuminance measurements must be recorded for the driver's side at points 1-13. The average illuminance at points 1-5 must be no less than 80 lux with the minimum measurement of these points no less than 13 lux; the average illuminance at points 6-9 must be no less than 30 lux with the minimum measurement of these points no less than 11.5 lux; and the average intensity at points 10-13 must be no

15   greater than 30 lux (to avoid glare). The illuminance measurements must be recorded for the passenger's side at points 14-26 and the average illuminance at points 14-18 must be no less than 80 lux with the minimum measurement of these points no less than 13 lux; the average illuminance at points 19-22 must be no less than 30 lux with the minimum measurement of these points no less than 11.5 lux; and the average illuminance at points 23-26 must be greater

20   than 30 lux.

Fig. 16 illustrates schematically how the light emitting assembly 10 of the present invention meets the above specifications. A section view is shown of a light emitting assembly

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10 similar to that of Fig. 1, but with five conventional discrete T 1-3/4 LEDs 14 (three amber

and two blue-green) illuminating a target surface at a distance R1, which is approximately 22

inches for an automotive interior mirror maplight. The points labeled T1-T7 represent

reference points on a target at which minimum and/or maximum illuminance requirements are

5   typically specified. The figure also illustrates overlapping beams from a plurality of two

different types of LEDs which are emitting light having complementary hues, *e.g.*, blue-green

and amber. The beams of the plurality mix as they travel outward from the LEDs,

overlapping to give a greater illuminance and form a binary-complementary additive color

mixture of metameric white light. It should be understood that, for some uses of the

10   illuminator of the present invention, such as a pocket flashlight, it is sufficient to use a

plurality consisting of a single amber LED and a single blue-green LED of the types described

above. Of course, other applications of the illuminator, such as an electric bicycle headlamp,

require many more of each type of LED in order to meet industry and regulatory

specifications.

15   An important criterion for an effective illuminator is that its projected light must

conform to accepted definitions of white light as previously described at reasonable operating

ranges. Inasmuch as the additive complementary color mixture of the present invention

depends on overlapping of projected beams from the member LEDs of the plurality in the

illuminator, it is important to understand that each illuminator of the present invention will

20   have a minimum operating distance for well-blended metameric white light. Depending on the

actual LED array and associated optics utilized in a given embodiment, this distance will vary

widely. Typically, good beam mixing (and thus balanced additive complementary light

combination to produce reasonably uniform white light) requires a minimum operating range of about 10 times the average distance between each LED and its nearest color complement in the plurality. This minimum operating range for good beam mixing is very dependent on the application requirements and optics used, however, and can be a much larger multiple of

5   complementary LED pitch spacing. For an automotive map light illuminator incorporated of the present invention as illustrated in Figs. 14 and 16 into an interior rearview mirror assembly, a typical dimension between complementary conventional discrete T 1-3/4 LEDs in the plurality is about 0.4 inches, and the minimum distance for reasonably uniform white illumination is about 12 inches. Since the specified target for this embodiment is 22 inches

10   away, this minimum operating range for uniform white illumination presents no problem.

It should be noted that the illuminator of the present invention does project illumination at ranges shorter than this specified range (as well as longer). The color and illuminance level of the projected light is typically not as uniform at shorter ranges, however.

The pitch spacing between LEDs, array size of the plurality of the LEDs in the

15   illuminator, and the characteristics of the collimating optics and diffusers used determine the distribution of constituent light in the illuminator's beam. Fortunately, these can be tailored to meet almost any desired combination of far-field intensity distribution, aperture, beam cut-off angle, color uniformity, and minimum operating range for effective uniform white illumination. For an electric bicycle headlamp, the predetermined distance for effective white

20   illumination may be 5 feet, and conventional discrete LEDs may be suitable as the plurality in the illuminator. For an instrument panel indicia backlight, however, the predetermined

distance for effective uniform illumination may be 0.25 inches or less and a chip-on-board

LED array using low f# lenslets will almost certainly be required.

Referring again to Fig. 16, the level of mixing of light from the five LEDs, as well as

the luminous output, depend on the distance R1 and also depend on the distance D between

5   complementary LEDs. If the LEDs in the plurality are packed closer together, the light mixes

completely at a shorter projected distance and the uniformity of the color and illuminance of

the combined beam is improved. The pitch spacing D between complementary LEDs in the

plurality can vary widely from approximately 0.020 inches (for a chip-on-board LED array) to

as much as 3 inches for a spotlight or greater for various floodlight applications, but is

10   preferably as small as possible. Conventional discrete LEDs often have their own integral

optical elements assembly, and therefore, there is a limit on how closely they can be packed

together. The five T 1-3/4 LEDs used to gather the above data were placed in a row

approximately 0.4 inches apart.

Irrespective of whether conventional discrete LEDs or individual dies are used, an

15   optical element should be incorporated into the illuminator assembly to direct the generated

light toward the desired surface and influence the distribution of the intensity generated by the

LEDs through the use of one or more of a lens, a diffuser, a reflector, a refractor, a

holographic film, etc. as discussed hereinabove.

For the automotive maplight illuminator of Figs. 14 through 20, two blue-green GaN T

20   1-3/4 LEDs from Nichia were operated at 24.5 milliamps and the three amber TS AlInGaP T

1-3/4 LEDs from Hewlett Packard were operated at about 35 milliamps. A 10° embossed

holographic Light Shaping Diffuser (LSD) from Physical Optics Corporation was used to smooth and distribute the illuminator beam.

Fig. 17 shows a perspective three-dimensional representation of the intensity distribution from an automotive interior maplight illuminator embodiment of the present invention. The Gaussian aspect of this plotted surface shows an important benefit of the present invention--that the intensity distribution of the illuminator is easily crafted to be a smoothly varying, monotonic function with respect to angular deflection from the primary optical axis of the illuminator. In contrast to this, many prior art illuminators are prone to intensity irregularities which can cause localized visibility distortions in the target area to be illuminated. Fig. 18 is a two-dimensional contour plot amplifying the intensity information given in Fig. 17 for the same illuminator.

In order for an illuminator to be effective, the projected beams from the plurality of light sources must overlap one another, such that, as discussed hereinbefore, a complementary color mixture occurs to produce metameric white light. In addition, the illuminator must project sufficient intensity in a desired direction to illuminate objects or surfaces at that distance to a light level where useful visual discrimination is possible, even in low ambient light conditions. Useful visual discrimination requires color contrast and luminance contrast between separate objects or images and this demands enough light for color vision to occur that is photopic or mesopic conditions. Photopic vision occurs when viewing objects or surfaces which have a surface luminance greater than approximately 5 candelas per square meter (5 nit), whereas Mesopic vision can reasonably be expected when viewing objects or surfaces which have a surface luminance greater than approximately 0.5 candela per square

meter (0.5 nit). For surfaces which are neutral gray, Lambertian, and have a reflectance

factor of 50 percent or more, Photopic and Mesopic levels of surface luminance will therefore

occur with illuminances of approximately 30 lumens per square meter (30 lux) and 3 lumens

per square meter (3 lux), respectively. For an illuminator 1 meter removed from this surface,

5   the required intensities for Photopic and Mesopic vision are therefore 30 candelas and 3

candelas, respectively. The relationships between intensity, illuminance, and luminance are

well known in the art and will not be discussed in further detail herein.

Fig. 19 shows the measured projected illumination pattern from the illuminator of

Figs. 17 and 18. The data shown were taken with a cosine-corrected illuminance meter from a

10   target whose center distance from the illuminator was 22 inches. The values shown, as for

those in Figs. 17, 18, and 20, represent initial values taken within approximately 30 seconds

of initial power-on. A comparison of Fig. 19 and Fig. 15 shows that the illuminator of the

present invention meets or exceeds the requirements of an auto manufacturer for an automotive

interior mirror map light. Note that the illumination level in the outer target zone which is

15   required to be less than 30 lux by the manufacturer is actually only about 7 lux in the case of

the present invention. This is accomplished without compromising the other minimum

illuminance requirements (such as in the target center which must be greater than 80 lux) and

illustrates the superior directional control achieved in the present invention. This provides a

significant safety advantage in that the light which is most distracting to the driver is much less

20   with the LED illuminator of the present invention than with a prior art incandescent light.

This advantage is also applicable to vanity mirrors, reading lamps, and dome lights because

the illuminator can be directed to where it is wanted and very little illumination goes where it

is not wanted. In summary, the LED illuminators of the present invention are more effective at placing light where it is desired and keeping it away from areas where it is undesirable.

Fig. 20 shows a simplified luminance map of a target surface with a hypothetical neutral gray Lambertian reflectance of 50 percent. Note the large area within which Photopic

5   levels of surface luminance are maintained. In the present invention, this zone also coincides with the minimum-sized zone within which the projected illumination possesses a metameric white color as previously defined. Thus, maximum color contrast and luminance contrast are made to coincide in the most critical central portion of the target area, giving observers the best visual discrimination possible.

10   The inventors have discovered that, outside of this effective Photopic white illumination zone (corresponding to Photopic levels of luminance for a 50 percent neutral gray target), substantial economy may be achieved by allowing the color of the additive mix to stray somewhat from accepted definitions of white. Surprisingly, outside of this zone, the color of the light from the illuminator is not as tangible to the unaided eye. This is apparently because

15   the capability for human vision to perceive colors falls off rapidly as surface luminance falls below the Photopic threshold into Mesopic and Scotopic conditions. Thus, for good color rendering and contrast, a white color should be projected throughout the Photopic illuminance zone and may also be for the surrounding Mesopic illumination zone. However, in order to economize (for instance in order to reduce the overall amount of LED light of a given hue

20   which must be produced and projected in peripheral areas of a target), the illuminator may be allowed to project slightly non-white colors into the surrounding Mesopic illuminance zone.

Although this Photopic threshold is commonly associated with a surface luminance of approximately 5 nit or greater, this can be translated to a corresponding "Photopic illuminance threshold" of approximately 30 lux for Lambertian surfaces with 50 percent neutral gray reflectance factor. A 50 percent neutral gray Lambertian reflector is a suitable reference

5 surface which represents, in a statistical sense, a high percentile of actual objects and surfaces to be illuminated.

Electronic control 122 energizes, protects, controls, and manages the illumination of the plurality of LEDs 14, 16, and 114 through circuitry. Although those skilled in the art will understand that there are a plethora of electronic circuits which can perform substantially the

10 same function, Fig. 21 illustrates the presently preferred circuit design for an automotive maplight.

Q1 and Q2 form a constant-current source. Q1's base current is supplied by the microprocessor Port 0 through current limiting resistor R2. Q2 regulates Q1's base current to maintain a substantially constant current through R1 and hence the amber LEDs D1-D3. The

15 regulation point is set by the cut-in voltage of Q2's base-emitter junction. A detailed explanation follows.

To energize LEDs D1 through D3, the voltage on Port 0 of the microprocessor U1 must be raised. This causes a current to flow into transistor Q1's base, $I_{b(Q1)}$, to increase. This will cause the collector current of Q1 to increase. Q1's collector current $I_{C(Q1)}$ and the

20 current through D1-D3 from the power supply V1 are substantially the same as the current through R1. This is because Q1's emitter current $I_{E(Q1)}$ is equal to the sum of its collector $I_{C(Q1)}$ and base $I_{B(Q1)}$ currents, and the base current is substantially smaller than the collector current

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(typically by a factor of 100). This can also be stated in equation form as follows (Equations 9-11).

$$I_{E(Q1)} = I_{C(Q1)} + I_{B(Q1)} \qquad [9]$$

$$I_{B(Q1)} << I_{C(Q1)} \qquad [10]$$

$$\therefore \quad I_{E(Q1)} \approx I_{C(Q1)} \qquad [11]$$

As the current through R1 increases, the voltage on Q2's base will increase. Once Q2's base-emitter cut-in voltage $V_{BE(Q2)}$ is reached, Q2's base current $I_{B(Q2)}$ will start to increase exponentially which will in turn cause an increase in Q2's collector current $I_{C(Q2)}$. Q2 will shunt current away from Q1's base, preventing further increases in Q1's collector current. The LED current is set at approximately $V_{BE(Q2)}/R1$ Ampere according to Equation 12.

$$I_{C(Q1)} \approx V_{BE(Q2)} / R1 \qquad [12]$$

(approximately 36mA at 25°C, with $V_{BE}=0.68V$ and $R=19$ Ohm). If the current through R1 should decrease for any reason, the voltage across R1 will decrease, reducing Q2's base current and in turn its collector current. This will allow more of the current supplied by the microprocessor U1 through R2 to flow into Q1's base which will increase its collector and emitter currents. This will tend to return the R1 current and hence the current through D1-D3 to its original value.

Because the emitter-base cut-in voltage of a silicon transistor such as Q2 decreases at a rate of approximately 2.5mV per degree Kelvin ($_\Delta V_{BE(Q2)}$), the current through Q1's emitter, collector and D1-D3 will decrease at a rate of approximately ($_\Delta V_{BE(Q2)}/R1$) Ampere per degree Kelvin (approximately 132$_\mu$A per degree Kelvin in this case).

Q3 and Q4 form another constant-current source. Q3's base current is supplied by the microprocessor Port 1 through current limiting resistor R4. Q4 regulates Q3's base current to maintain a substantially constant current through R3 and hence the blue-green LEDs D4-D5. Operation of this current source is substantially the same as the current source which drives

5   the amber LEDs (D1-D3). In the present design, two current sources are used to accommodate the different maximum current ratings of the blue-green and amber LEDs as well as to allow independent duty cycle control and hence illumination intensity of the two colors. Some applications may allow the use of a single current source or a simple current limiting resistor and/or the series connection of the blue-green and amber LEDs. Multiple

10   current sources may also be required if the forward drop of a series string of the required number of LEDs approaches the supply voltage too closely.

This temperature-dependent current drive allows the LEDs to be driven at or very near their maximum forward current during normal (cool) conditions, and as the temperature rises, there is no risk of overloading the LEDs. Fig. 22 shows the specified maximum forward

15   current versus temperature for the preferred amber LEDs as well as the experimentally determined forward current versus temperature plot for the LEDs of the present invention in the above-described circuit. As can be clearly seen, the LEDs can be operated at approximately 42 mA at -40°C, at approximately 36 mA at 25°C, and at 31 mA at 85°C . Thus, the LEDs are operated very near their maximum forward current at low temperatures,

20   and the above-described circuitry will automatically adjust the forward current of LEDs D1-D5 to stay within the specification as the temperature rises up to 85°C. Thus, by utilizing the circuitry shown in Fig. 21, the output from the LEDs is maximized during periods of

minimum ambient light when the illuminator will predominantly be used (it is typically coolest

at nighttime) and decreases during maximum ambient light, *i.e.*, daylight, when the

illuminator would not generally be used (it is typically hottest during the day). In order to

maximize the benefit of the LED illuminator and minimize the cost and complexity required to

5   achieve that benefit, it is very important to operate them at or very near their maximum

allowed current rating for the prevailing temperature conditions.

One prior method for avoiding thermal overload of these LEDs when operated at high

operating temperatures was to permanently de-rate the LED to run at a non-varying current set

at a lower level within that specified for the LED at the maximum specified operating

10   temperature, *e.g.*, 25mA at 80°C. However, this significantly reduced the luminous output at

low temperatures when the LED could be driven harder (and have more output) without

damaging the LED if a more capable circuit was employed.

Another prior method utilized a thermistor in the circuit that measured the ambient

temperature and automatically de-rated the LEDs at higher temperatures; however, this

15   complicated the circuit design and, more importantly, substantially increased the cost of the

circuit.

The circuit of the present invention is a novel and inexpensive (and therefore

commercially viable) method of ensuring that the maximum allowed LED output is achieved at

all operating temperatures and achieving nearly a 70 percent increase in luminous output at

20   typical nighttime temperatures as compared to less sophisticated circuits.

LEDs have an operating current of approximately 30-70 mA which is much lower than

the typical incandescent lamp operating current of approximately .35 amps up to many amps.

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This lower operating current allows the use of inexpensive bipolar transistors Q1 to Q4, such as, for example, MPSA06, for the LED drivers which are much cheaper than the Metal Oxide Semiconductor Field Effect Transistors (MOSFET) required in an electronic control circuit for an incandescent lamp. In addition to decreasing production costs, the bipolar transistors of the

5   present invention automatically de-rate the LEDs as the ambient temperature increases.

As those skilled in the art will realize, the microprocessor U1 can manage and manipulate the output from LEDs D1-D5. For example, by removing any voltage from port 0, the base voltage to Q1 will be zero and no light will be emitted from D1-D3 and only light emitted from D4-D5 will illuminate the interior of the vehicle. Similarly, the voltage from

10   port 1 can be removed and only amber light will illuminate the interior of the vehicle. Of more practical importance is that the emission of either LEDs D1-D3 or D4-D5 can be modulated by the microprocessor U1 by modulating the base currents to Q1 and Q3, respectively. Furthermore, the "amount" of amber light generated from D1-D3 relative to the amount of blue-green light (or other combinations if different LEDs are chosen in accordance

15   with the above metameric teachings) can be varied simply by controlling the modulation of voltage out of ports 0 and 1. Controlling this proportion is especially important in maplights because the properties of the vehicle interior, e.g., colors and dimensions, may warrant a slightly different "white" color emission from the illuminator to maintain maximum readability. By allowing pulse-width modulation, the present circuit design allows for

20   modulation data to be stored in non-volatile memory U2 and easily changed depending on which automobile the mirror assembly will be installed. In addition, time sequential multiplexing allows D1-D3 and D4-D5 to be turned on and off rapidly one after another, such

that they are never actually on at the same time. The illumination produced in this fashion is still achromatic and effective because the time constants for human visual response are so slow that the human eye cannot discern the rapidly changing color of the illumination projected by the color-complementary LEDs in the illuminator energized in rapid sequence. In the case of the present LED illuminator, the on/off times can be very fast and the sequencing frequency very high, because LEDs do not suffer from bloom time limitations. Additive mixing occurs and therefore the light from the illuminator in the vehicle looks white, even with a minor time delay between the presence of illumination from the two additive constituents of the mixture.

In addition to manipulating color, the microprocessor U1 can pulse-width modulate the LED currents for purposes of thermal de-rating. A microprocessor U1 with internal or external temperature measurement means can modulate the LED currents to very precisely follow the manufacturer's specified current ratings at each temperature as illustrated by the curve in Fig. 22 labeled "Design Current for Software-Controlled Temperature Compensation." In the case of microprocessor controlled thermal de-rating, the current limiting means must provide a current greater than or equal to the maximum of the design current for software control. For the amber LEDs D1-D3 in the example in Fig. 22, the current limiting means must provide at least 48mA. This would require changing the value of R1 in Fig. 21 to 14 Ohm. At 70∘C, the microprocessor U1 would begin pulse-width modulating the current through D1-D3 in Fig. 21 to reduce the average current to safe levels using a lookup table, calculation or other means to determine the correct duty cycle. Alternatively, R1 in Fig. 21 could be set to 10 Ohm for a 68mA drive current and the duty cycle set at 70 percent to maintain an average current less than the manufacturer's limit.

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Obviously, there are an infinite number of current and duty cycle combinations that can be used to maintain the required average current as long as the peak drive current does not exceed the LED manufacturer's peak current ratings.

The invention has been described in detail for a rearview mirror incorporating an illuminator. However, those skilled in the art will realize that the illuminator of the present invention may be used in other vehicular applications such as dome lights, vanity mirror lights, headlamps as well as engine and trunk compartment lights. A dome light assembly or a vanity mirror assembly incorporating an illuminator according to the present invention will have a housing, one or more lenses, and an electronic control in accordance with the above teachings. Any slight modifications to the housing, lenses, and electronic control will be clear to those skilled in the art. In addition to vehicular embodiments, the present invention may be used in non-vehicular embodiments requiring high efficiency, high reliability, long life, low-voltage compact, effective white-light illumination as well without diverting from the present teachings. Such applications include hand-held portable flashlights, head- or helmet-mounted lamps for mining or mountaineering, task lighting for volatile environments where explosion is a hazard, illuminators mounted in difficult to maintain areas such as atop buildings, automatically activated emergency lighting or back-up lighting in commercial buildings, and microscope stage illuminators to name a few. Again, the minor modifications to the housing, lenses, and electronic control will be clear to those skilled in the art and, therefore, it should be understood that these vehicular and non-vehicular illuminator uses fall within the scope of the present invention.

Although the present invention has been described generally with respect to illumination, and more specifically with respect to a map lamp illuminator for incorporation in a rearview mirror assembly, it will be appreciated by those skilled in the art that the light emitting assembly of the present invention may be used for any application in which a light

5   source would otherwise be used. Such applications may include not only illumination applications, but also applications in which a light source is used as, or as a part of, an indicator. The light emitting assembly of the present invention may also be used for back-lit displays. Commonly assigned U.S. Patent Application No. 09/425,792 entitled "INDICATORS AND ILLUMINATORS USING A SEMICONDUCTOR RADIATION

10   EMITTER PACKAGE," filed on October 22, 2000, by J. Roberts et al. discloses several uses of LED assemblies. The light emitting assembly of the present invention may be used in some or all of these applications. The entire disclosure of U.S. Patent Application No. 09/425,792 is incorporated herein by reference.

Although the present invention has generally been described as using two or more light

15   sources where one or more of the light sources may be a fluorescent dye or phosphor, it will be appreciated by those skilled in the art that other photoluminescent light sources may be used, such as fluorescent or phosphorescent materials used in fluorescent lighting. Thus, according to some embodiments of the present invention, the mixing of two phosphors that each emit light of different hues and whose emitted light overlaps and forms effective white

20   light, would fall within the scope of the present invention.

While the invention has been described in detail herein in accordance with certain preferred embodiments thereof, many modifications and changes therein may be effected by

those skilled in the art without materially departing from the novel teachings and advantages of

this invention. Accordingly, all such modifications are intended to be included within the

scope of this invention as defined in the following claims and, therefore, it is our intent to be

limited only by the scope of the appending claims and not by way of the details and

5   instrumentalities describing the embodiments shown herein.